Towards a Sampling and Monitoring Protocol of Radioactive Elements in Fractured Rock Aquifers for Groundwater Resource Security in Beaufort West

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

The Water Research Commission (WRC) granted a project, i.e. K5/1694/1, to a consortium of researchers led by the University of the Western Cape, to develop a sampling and monitoring protocol for radioactive elements in fractured rock environments. As the protocol had to be based on the international best practice and linked to a local case study where the sustainable utilization of groundwater resources was essential, the deliverable was eventually accepted by the Reference Group to be composed of 5 deliverables, namely:

- Literature survey of existing protocol and guidelines and related water supply issues
- Local sampling and monitoring protocol for radioactive elements in fractured rock aquifers in South Africa
- Aquifer characterisation and groundwater flow regimes of Karoo aquifers in Beaufort West, Western Cape Province
- Groundwater source protection in a fractured rock aquifer: A case study in Beaufort West, South Africa
- Final report.

The project was closely guided by the Reference Group with the following project activities completed in phases and key issues identified:

Phase I: The first phase of the project focused on a literature review of radioactivity in groundwater and compiling a database on the physico-chemical characteristics of radioactive elements.

Phase II: A hydrocensus of the study area was undertaken in order to assess the water resources utilization of the Beaufort West Town and its surroundings, to characterize the aquifer system and to delineate the groundwater flow regimes of the aquifers in the area. The hydrocensus showed that in terms of groundwater radioactivity the presence of uranium mines presented a major potential impact. A follow-up hydro-census was conducted, especially to the south of the town in the vicinity of the mines in order to establish baseline pre-mining conditions. Based on data and information available, no evidence of uranium contamination was established in any of the boreholes sampled during this project.

Phase III: The data and information of the first two phases was used to set up a practical sampling and monitoring protocol for radioactive elements for use in southern African fractured aquifers.

Phase IV: A need was identified for a proactive approach to protect Beaufort West's groundwater resources from potential contamination that would to a large degree avoid the costly and technologically difficult exercise of groundwater remediation. As a part of the final phase of the project, an aquifer protection zoning was recommended for implementation.

The present report summarises all the activities leading from a survey of the hydrology of the Beaufort West area to the radioactive protocols needed for proper evaluation of the threats posed to the water resources of the town by uranium mines in the south of the well fields and paving the way forward.

Key Issues

During the project, the available existing data were collated into a database in the form of spreadsheets that are attached in the Appendices of this report. The information was derived from a variety of sources cited in the reference list.

The sampling and monitoring for radioactive elements in fractured rock aquifers in South Africa should consist of pre-sampling procedure like borehole selection, borehole purging, appropriate devices and reporting. Sampling hole location, for instance, must be able to reflect intended uraniferous formations. As there is the extensive alluvial cover on top of the Teekloof Formation, the sampling hole should be in the bedrock comprising mudstones, siltstones and sandstones. In addition, flow regime should also be considered, as a sample should represent the uranium concentration of specific formation water flows through. Determination of hydrogeological condition remains essential.

As illustrated in the Beaufort West case study, background radioactivity was generally acceptable except for few samples, which were anomalously high. Taking cognisance of the methods used, as well as those previously applied in the area and abroad, the sampling protocol for radioactive elements in fractured rock aquifers was conceptualized and developed for local adoption and further improvement in due course if necessary. The adapted protocol applied in the case of Beaufort West is documented in this report. A functional chart of the protocol is also provided to guide the user through the proposed protocol.

As a recommendation it was suggested that multiple methods be tested in the boreholes or wells of interest in order to check whether similar results would occur. This would thus determine the best applicable methods. It could also be clearly seen, by comparing historical data and the current data, that the methods used for sampling heavy metal can be applied to radioactivity.

In order to delineate wellhead protection zones, the specific land and geographic area should be included in the protection zoning program. As fractured rocks usually offer less opportunity for natural attenuation or degradation of contaminants than do porous rocks and U like all heavy metals, not being particularly biodegradable, many fractured aquifers can transport the contaminants rapidly for long distances with little attenuation of the contaminants, which was manifested in a tracer test carried out in the project. Important factors that need to be considered for protection zoning in fractured rock environments are, first, a clear understanding of the purpose and scale of the desired protection and, second, a clear and accurate conceptual model of the local groundwater system. This can be used as a basis for further in-depth numerical modelling to identify the importance of different types of dykes and faults and the 0's

As compartments are isolated from each other, the protection of water yielding compartments becomes a top priority. Instead of focus on detail simulation for delineation of capture zones within a compartment, emphasis is placed on how to conceptualize a protection zone in fractured rock aquifer in general and particularly in Beaufort West. Guiding criteria for numerical zoning simulation have been established. Two sets of criteria, e.g. Volume and Penetration factors, are proposed for determination of whether or not a 2D or 3D model should be used for the protection zoning. These criteria involve parameters including R (recharge), Q (abstraction), and P (borehole penetration of aquifer), etc. The proposed criteria were tested and verified through actual simulations.

In addition to protection against conventional contaminants like pathogenic bacteria and nitrate, a thought was given to the possibility of contamination from uranium waste sites. As uranium mining occurs mainly to the southwest, south and southeast of Beaufort West, a worst case scenario was discussed. Due to the inaccessibility of most of the properties in these areas, the study area is practically limited to areas where data is available. This area includes the town well fields in the north and northeast (up to 40 km northeast of town), 40 km east of the town including the farm Sunnyside, 30 km south of the town up to the farm Blydskap. Note that the southern areas have large gaps in data since most of these properties were strictly prohibited from being entered. Therefore the worst scenario was hypothesized and discussed for precautious purpose.

Judging from historical point of view, water demand in Beaufort West has been expanding. In addition to the 4 municipal wellfields, more wellfields are being developed to augment the current groundwater supply. A groundwater protection strategy must be incorporated in any water supply strategy and a holistic water safety plan should be developed under an IWRM framework.

Finally, it is recommended that the monitoring procedure presented in this report should be fully implemented and incorporated in a Water Conservation and Water Demand Management Strategy for the municipality of Beaufort West if and where necessary.

ACKNOWLEDGEMENTS

Our vote of thanks goes to the Reference Group for the Water Research Commission (WRC) Project K5/1694, and all the members of the Group who guided the project for the sampling and monitoring protocol for radioactive elements in fractured rock aquifers. Our special thanks are given to Messrs Mannie Levin and John Weaver of the Group who provided critical and constructive comments in a written format. Members of the Reference Group consist of the following:

- Dr Shafick Adams (Water Research Commission – Chairperson)
- Dr Mannie Levin (Geo Africa)
- Mr Siep Talma (Former CSIR research scientist)
- Mr John Weaver (Former CSIR research scientist)
- Dr Danie Vermeulen (IGS – University of the Free State)
- Dr Eddie van Wyk (DWA)

Mr Regan Rose from GEOSS and Dr Kevin Pietersen (Water Geoscience Consulting) are acknowledged for their partial participation in the project. The project benefited from various meetings with the staff of Bellville Office of the Department of Water Affairs, especially Messrs Piet Havenga, Paul Seward and Mike Smart who provided the project team with valuable data and information on Beaufort West aquifers.

Furthermore the people of Beaufort West, as well as the municipality, also deserve gratitude. In particular Mr Louw Smit, for his assistance and willingness to assist wherever he could, is gratefully acknowledged. They have all aided in the completion of this project and contributed greatly towards creating a better understanding of the study area.

As specifically requested by the WRC, the research team has gone through serious capacity building process. As a result, many students, especially post-graduates at the University of the Western Cape and the University of Pretoria, have had exposure to the field work to various extents. Two MSc students graduated as a direct result of their enthusiastic involvement in the project.

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Abbreviations

CGS	Council for Geoscience
ch	collar height
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry (now DWA)
GRA II	Groundwater Resource Assessment Phase II (DWAF 2005)
GS	South African Geological Survey (now CGS)
GH report	Geohydrology report at the DWA
IAEA	International Atomic Energy Agency
m	metres
Ma	Million years
mamsl	metres above mean sea level
mbch	metres below collar height
mbgl	metres below ground level
mS/m	milliSiemens per meter
mSv/a	milliSievert per year (a descriptor of effective dose rate)
mg/l	milligrams per litre
NECSA	The South African Nuclear Energy Corporation
NGDB	National Groundwater Database
U	Uranium
UWC	University of the Western Cape
WGS84	Since the 1st January 1999, the official co-ordinate system for South Africa is based on the World Geodetic System 1984 ellipsoid, commonly known as WGS84, with the ITRF91 (epoch 1994.0) co-ordinates of the Hartebeesthoek Radio Astronomy Telescope used as the origin of this system. This new system is known as the Hartebeesthoek94 Datum.
WISH	Windows Interpretation System for Hydrogeologists
WMS	Water Management System
WRC	Water Research Commission

Conversions

1 µg/L (ppb) ^{238}U = 12.4 mBq/L,
1 µg/L (ppb) ^{235}U = 79.7 mBq/L
1 µg/L (ppb) ^{232}Th = 4.0 mBq/L.

1. INTRODUCTION

1.1 Background

The issue of radioactive pollution of groundwater in South Africa was first raised in 1967 (Stoch, 2008, Winde, 2010). As reported by Winde (2010), in U-mining areas, where U is liberated from the lithosphere at faster accelerated rates than that in nature, the high aquatic mobility of U frequently results in large-scale pollution of groundwater and surface water. In a WRC project conducted by Toens et al. (1998), the authors reported a correlation between elevated U levels in drinking water from boreholes and abnormal haematological values linked to leukaemia. In the light of possible demand for the U mining in South Africa, sampling and monitoring of the U element in borehole water needs to be assessed for the purpose of water security.

The Water Research Commission (WRC) awarded a project (K5/1694/1) to a consortium of researchers led by the University of the Western Cape to develop a sampling and monitoring protocol for radioactive elements in fractured rock environments. The consortium of researchers consists of council of Geoscience (CGS), Water Geoscience Consulting (WGC), and University of the Western Cape (UWC). GEOSS was asked by the WGC to complete a research deliverable initially assigned to WGC. University of Pretoria was involved in the project at a later stage to continue what started at CGS due to a researcher's resignation from CGS for the university. The research outcomes are to support the implementation of the "National Radioactive Monitoring Programme". The specific deliverables of WRC project K5/1694/1, as adapted in the course of the project, are as follows:

a) Re-evaluate the results of earlier research findings on uranium speciation and the associated anomalies (i.e. anomalies in the aqueous environment) at the selected study area. This deliverable constitutes Deliverable 1 of the project and includes the literature and database review on physical-chemical characteristics of radioactive elements as well as a hydrocensus.
b) Applying recent advances to characterize flow regimes in fractured rock aquifer systems, with reference to 'tracing' the distribution of radio-active elements in fractured media. This deliverable constitutes Deliverable 2 of the project and includes the aquifer characterisation and delineation of groundwater flow regimes.
c) Development of local-scale sampling and monitoring protocol for radioactive elements in fractured rock formations. This deliverable constitutes Deliverable 3 of the project.
d) Delineating a groundwater protection zone around a selected water point with respect to an unstressed system taking into account the hydraulics, behaviour of selected radio-active elements, relevant policy documents, etc. This deliverable constitutes Deliverable 4 of the project.

During the project, a number of field investigations were conducted in order to understand and verify local hydrogeological settings. Beaufort West is a drought prone area with a mean annual precipitation of about 225 mm. As a result of on-going exploratory drilling and monitoring commissioned by the DWAF and Beaufort West Municipality starting in the 1970s to present day, geohydrological related data should be readily available for this area. The occurrence of radioactive elements in the Karoo Supergroup was first detected in the Karoo in 1964 during kimberlite exploration (Uramin, 2006). Early in 1970, an American exploration company embarked on systematic search of uranium in the Karoo, which resulted in the discovery of uraniferous sandstone on a farm, Grootfontein 180, 20 km west of Beaufort West (Uramin, 2006). Subsequently, uranium mineralisation was discovered on the farm Ryst Kuil (40 km south of Beaufort West) in 1973. The Geological Survey of South Africa undertook a detailed aerial-radiometric survey, which commenced in 1976, to delineate major U occurrences in the Main Karoo Basin. This resulted in the subdivision of the main Karoo U Province into ten uraniferous provinces (Uramin, 2006). Despite a potential health hazard imposed by uranium waste to groundwater, which provides more than 50% of the total water supply for the town, no protection measures were ever initiated.

This is the final report of the project that deals with sampling and monitoring of radioactive elements in aquifers for groundwater security in Beaufort West area. It supports the project objective of securing groundwater supply in Beaufort West within the broader WRC project objectives mentioned above.

For the purpose of sustainable water supply in Beaufort West South Africa, the following three questions need to be answered;

(1) how much groundwater is needed for the town?
(2) is the water for community supply safe and how to manage it for security reason?
(3) is infrastructure (pump design, water tanks, reticulation) reliable, in the light of hydrological variability?

Question (1) is directly related to the size of local community and the level of services the local municipality is prepared to commit according to the Water Services Act of 1997. Question (3) is largely taken care of by the municipality. This report is only focused on question 2, which deals with good groundwater quality, that is potable.

Freshwater from boreholes and springs is the prime example of a renewable natural resource. However, this resource is under constant threat, especially as a result of population expansion and hydrological variability. One of the most obvious ways to waste this resource, is groundwater contamination. Therefore, assessing potential sources of contamination by sampling and monitoring of radioactivity in local aquifers is a pre-requisite for groundwater protection. The delineation of borehole/spring protection zones and the implementation of proper land-use practices in these zones, resulting in a reduction of polluting activities, are keys to the sustainable use of these valuable drinking water resources.

In Beaufort West boreholes are often sited in or along permeable dykes or single fracture zones through which aquifers are drained as observed in the Karoo. It therefore becomes important to take into account dyke-influenced aquifers. This report makes use of local dyke characteristics for formulation of groundwater sampling, monitoring and protection recommendations in a fractured rock aquifer, which would be seen as reinforcement of the Resource Quality Objectives, one of three cornerstones for sustainable management of water resources including groundwater in South Africa.

1.2 Radioactivity

The major natural radionuclides that may present in groundwater are uranium, radium and radon, and to a lesser extent polonium, thorium and lead. All of these are products of the three known decay chains headed by ^{238}U, ^{235}U and ^{232}Th (Figure 1). The difference in half-lives and varying solubility of each radionuclides under different circumstances, determine the wide variety of activity levels found in rock, soil and water. Most of the radio-nuclides are metals and behave as such in water, though many complexes are formed as will be evident from the discussion of uranium. ^{222}Rn is a gas and high levels may be present in freshly pumped groundwater. Although it is a serious cancer risk due to its daughters settling in the lungs, its short halflife (3.6 days) and rapid escape from open water bodies ensures that it is not relevant for most water use application.

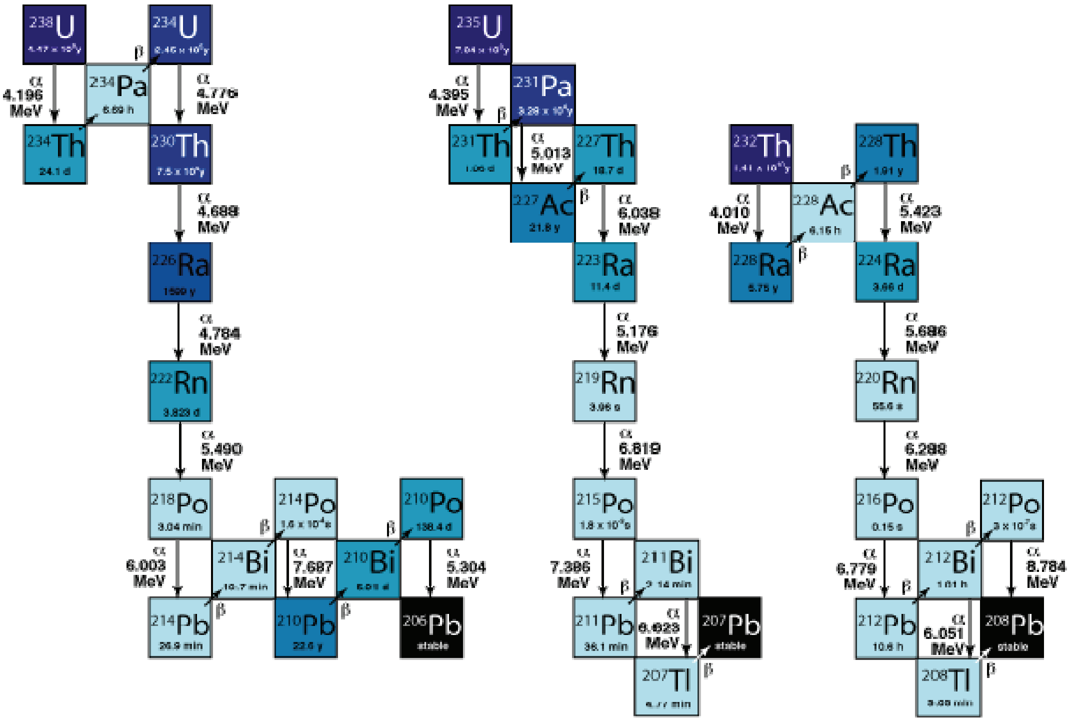


Figure 1: Depiction of the three decay chains found in nature (Wikipedia Web Dictionary). Darker blocks represent longer half-lives.

Natural uranium occurs in the 2^{+}, 3^{+}, 4^{+}, 5^{+} and 6^{+} valence states, but is most commonly found in the hexavalent form. Major compounds of uranium include oxides, fluorides, carbides, nitrates, chlorides, acetates, and others. Leaching of uranium into (surface and ground) water takes place depending on the redox state, the pH, temperature and the chemical composition of the water. This is indicated by the stability diagram (Figure 2). In general, higher redox, lower pH and more dissolved carbonate will enhance dissolution of uranium. Reversal of this process can occur when conditions change, thereby causing uranium to precipitate.

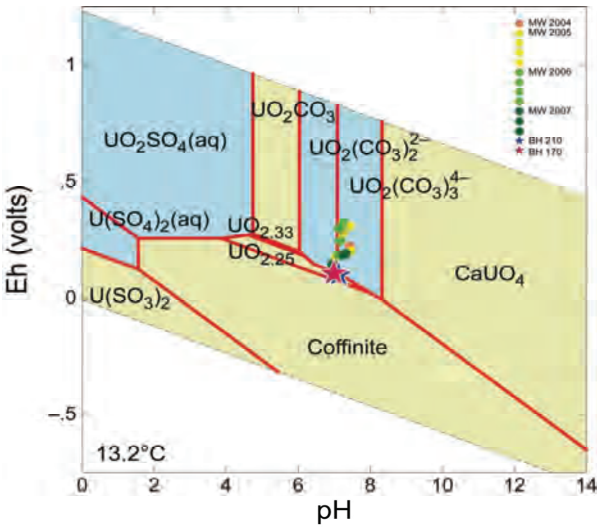


Figure 2: Uranium speciation (Pourbaix) diagram in the presence of carbonate and sulphate (from Zeman, pers comm., 2010).

The average crustal abundance of uranium is about 2 to 3 ppm. Naturally occurring uranium is a mixture of three radionuclides (^{238}U, ^{235}U and ^{234}U), all of which decay by both alpha and gamma emissions. The mass distribution of the three isotopes is 100: 0.73: 0.01-0.05 which becomes relevant for chemical studies. The activity distribution is 100: 4.5: 100-500 and indicates that for radiological consideration ^{234}U is very relevant. In old undisturbed rock the activity ratio of $^{234}U/^{238}U$ is 1, following the principle of radioactive equilibrium. During uranium dissolution in groundwater there is a preference for ^{234}U to dissolve more rapidly than ^{238}U. Groundwater is therefore characterised by a $^{234}U/^{238}U$ activity ratio of 2 and greater. If however, uranium is dissolved by chemical means, as will be the case in mining conditions, the activity ratio will remain unity. This feature has been applied to distinguish the source of uranium in water (Kronfeld and Vogel, 1991).

Thorium is generally very insoluble in water and thus of minor concern. Radium is more soluble and behaves very much like calcium and magnesium (being in the same column of the periodic table).

1.3 Radioactivity in drinking water

The human body has a tendency to expel a fraction of the ingested heavy metals. However some will remain and be located in certain organs. Drinking water can constitute an important pathway of non-occupational exposure to radionuclides (Smedley et al., 2006). In general the effects of exposure to elevated levels of radioactivity in the body are an increase in the cancer risk due to

DNA damage caused by radiation. The organ at risk for cancer will depend on the site in the body where the radionuclide resides, which is determined by the chemistry of the radionuclide.

Uranium tends to accumulate in the kidneys and the liver where its chemical damage can cause renal failure (WHO, 2011). In the case of radon and its short-lived daughter nuclides, the primary target organ is the lungs and the risk is presented via inhalation of air contaminated with radon. This may occur on showering with radon-rich water in a poorly ventilated area. For radium and thorium the target organ is the bony skeleton, because of the insolubility of the phosphate salts. Little is known of the radiological effects of lead-210 and polonium-210.

The laboratory of NECSA reports analytical results of radionuclide analysis in water as (example in Appendix A Table 8):

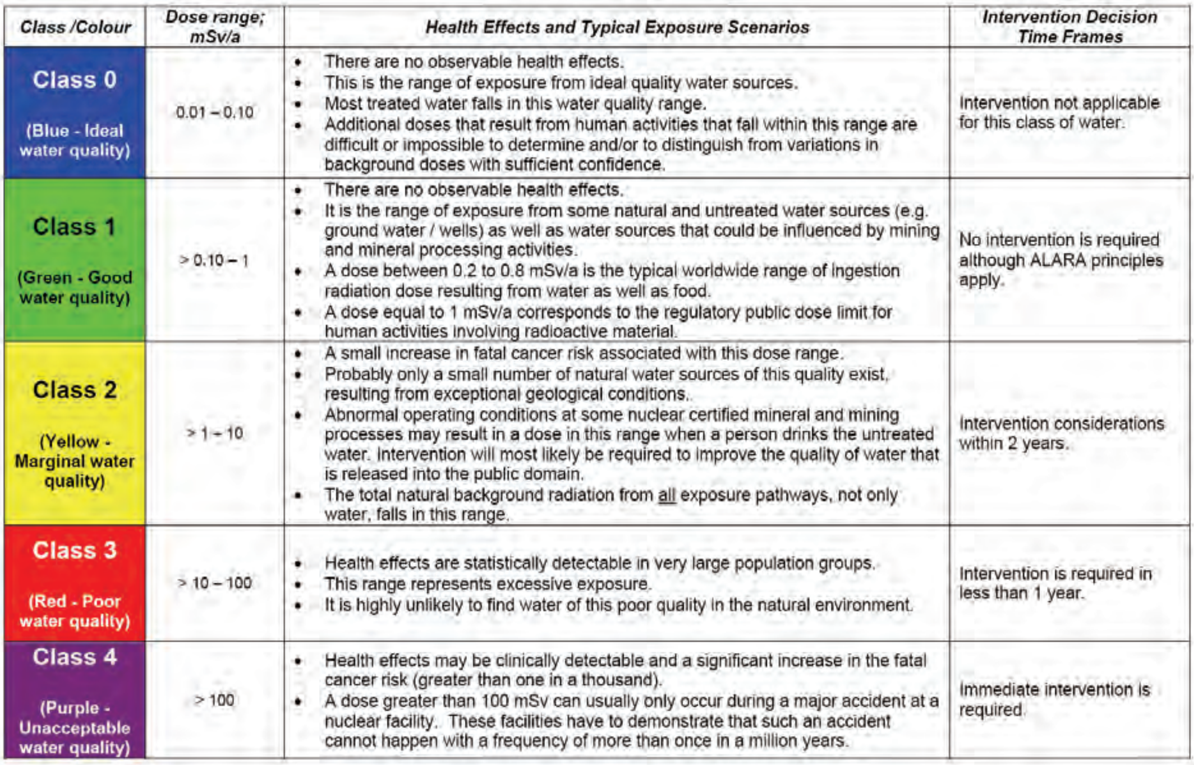
- Result in Bq/L;
- Uncertainty (unc) in Bq/L;
- Minimum detection activity (MDA) in Bq/L.

This should be interpreted as:

If Result<MDA, then the activity of the sample is "<MDA"

If Result >MDA, then the activity of the sample is "result ± UNC". This means that there is a 66% probability that the 'true' value is within this range.

Table 1: Radiological guidelines for drinking water (ALARA = "As Low As Reasonably Achievable") (SANS 241, 2011)



Class /Colour	Dose range; mSv/a	Health Effects and Typical Exposure Scenarios	Intervention Decision Time Frames
Class 0 **(Blue - Ideal water quality)**	0.01 – 0.10	• There are no observable health effects. • This is the range of exposure from ideal quality water sources. • Most treated water falls in this water quality range. • Additional doses that result from human activities that fall within this range are difficult or impossible to determine and/or to distinguish from variations in background doses with sufficient confidence.	Intervention not applicable for this class of water.
Class 1 **(Green - Good water quality)**	> 0.10 – 1	• There are no observable health effects. • It is the range of exposure from some natural and untreated water sources (e.g. ground water / wells) as well as water sources that could be influenced by mining and mineral processing activities. • A dose between 0.2 to 0.8 mSv/a is the typical worldwide range of ingestion radiation dose resulting from water as well as food. • A dose equal to 1 mSv/a corresponds to the regulatory public dose limit for human activities involving radioactive material.	No intervention is required although ALARA principles apply.
Class 2 **(Yellow - Marginal water quality)**	> 1 – 10	• A small increase in fatal cancer risk associated with this dose range. • Probably only a small number of natural water sources of this quality exist, resulting from exceptional geological conditions. • Abnormal operating conditions at some nuclear certified mineral and mining processes may result in a dose in this range when a person drinks the untreated water. Intervention will most likely be required to improve the quality of water that is released into the public domain. • The total natural background radiation from all exposure pathways, not only water, falls in this range.	Intervention considerations within 2 years.
Class 3 **(Red - Poor water quality)**	> 10 – 100	• Health effects are statistically detectable in very large population groups. • This range represents excessive exposure. • It is highly unlikely to find water of this poor quality in the natural environment.	Intervention is required in less than 1 year.
Class 4 **(Purple - Unacceptable water quality)**	> 100	• Health effects may be clinically detectable and a significant increase in the fatal cancer risk (greater than one in a thousand). • A dose greater than 100 mSv can usually only occur during a major accident at a nuclear facility. These facilities have to demonstrate that such an accident cannot happen with a frequency of more than once in a million years.	Immediate intervention is required.

Table 2: Threshold values for uranium in drinking water.

Authority	**U threshold (mg/L)**	**Remarks**
SANS (2011)	<0.015	Guideline
WHO (2011)	<0.030	Guideline
DWAF (2002)	<0.070	No significant risks. Annual cancer risk less than one in four million
	0.070-0.284	Annual cancer risk less than one in a million. Potentially a slight risk of renal toxicity in sensitive individuals where renal functions is impaired, but unlikely to have demonstrable renal toxicity in healthy individuals.
	0.284-1.42	Annual cancer risk less than one in 200 000 but significant risk of chemical toxicity with renal damage
	> 1.42	Increasing cancer risk in the long term. Increasing risk of renal damage in the short term

For any chronic exposures to radiation, the most important parameter that needs to be known is the radiation dose (DWAF 2005), which is expressed in milliSievert per annum (mSv/a). This represents the energy absorbed in the body and its likely biological damage effect. The effect is different for each radionuclide. The total dose rate to which an individual has been exposed is the sum of the dose rates from each radionuclide. (DWAF, 2002). The average human radiation exposure due to all natural background sources amounts to approximately 2.4mSv/a (WHO, 2011). The recommended reference dose level (RDL) for drinking water of 0.1mSv/a given by the World Health Organization (WHO) and adapted by the South African water quality guidelines, is only 5% of the dose from the total natural background, and is therefore very conservative. The South African guidelines for radiological quality in domestic water are given in Table 2. The chemical water quality guidelines of various authorities with respect to uranium are given in Table 1. The differences are due to different opinions on what constitutes acceptable risk.

1.4 Study area selection

Initially, the proposed study area was in Steenkampskraal in Northern Cape, however a recommendation was made by the Reference G to look at Beaufort West as a study area due to the accessibility of data and more importantly the crises the town faces in terms of severe water scarcity, potential uranium mining and the contentious issue of hydraulic fracking.

Beaufort West suffers from a drastic shortage of water supply from time to time, causing a major concern about its local water security among the stakeholders and community. This situation may be further impacted by groundwater contaminations by all sources including uranium as outlined above. This recommendation was duly accepted and implemented by the research team.

The criteria used for the selection of Beaufort West are discussed in detail under the section 2.3 of this report.

2. BEAUFORT WEST STUDY AREA

2.1 Geological framework

The occurrence of radioactive elements in the Karoo Supergroup was first detected in the Karoo Group in 1964 during kimberlite exploration. Early in 1970, a US exploration company embarked on a systematic search of for uranium in the Karoo. This resulted in the discovery of uraniferous sandstone on a farm, Grootfontein 180, 20 km west of Beaufort West (Cole et al., 1991). Following this discovery, the Geological Survey of South Africa undertook a detailed aero-radiometric survey in 1976, to delineate major uranium occurrences in the Karoo Main Basin. This survey resulted in the subdivision of the main Karoo uranium province into ten uraniferous provinces (Figure 3).

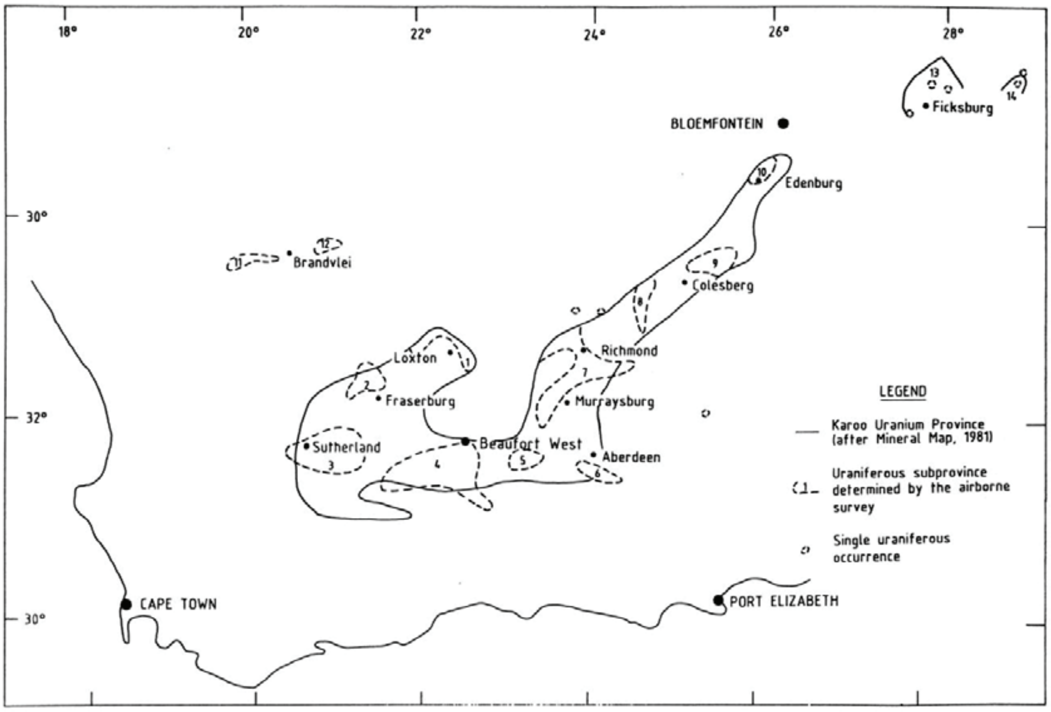


Figure 3: Uraniferous regions in the Karoo Uranium Province (Cole et al., 1991).

The Karoo Basin is a Late Carboniferous-Middle Jurassic retroarc foreland basin developed in front of the Cape Fold Belt (CFB) in relation to subduction of the palaeo-Pacific plate underneath the Gondwana plate (Catuneanua et al., 1998). These were infilled with up to 12 km of sedimentary strata of the Karoo Supergroup (Figure 4). The sedimentary succession reflects changing depositional environments from glacial to deep marine: deltaic, fluvial and Aeolian, and is subdivided into five main groups (Catuneanua and Elango, 2001), namely, Dwyka, Ecca, Beaufort (comprising the Adelaide and Tarkastad subgroups), Stormberg and Drakensberg.

Most of the uraniferous occurrences are located in the fluvial-channel sandstones of the Adelaide Subgroup of the Beaufort Group. The Adelaide Subgroup consists of alternating bluish-grey, greenish-grey or greyish-red mudrock and grey, very fine to medium-grained lithofeldspathic sandstone (Woodford and Chevallier, 2002). Palaeocurrent data indicate that the bulk of the sediment was derived from a source area situated to the south and southeast of the Basin, with subordinate influxes from the southwest, west-northwest and northeast (Woodford and Chevallier, 2002). The sandstones represent river channel deposits (fluvial) and the mudstones represent floodplain deposits (lacustrine).

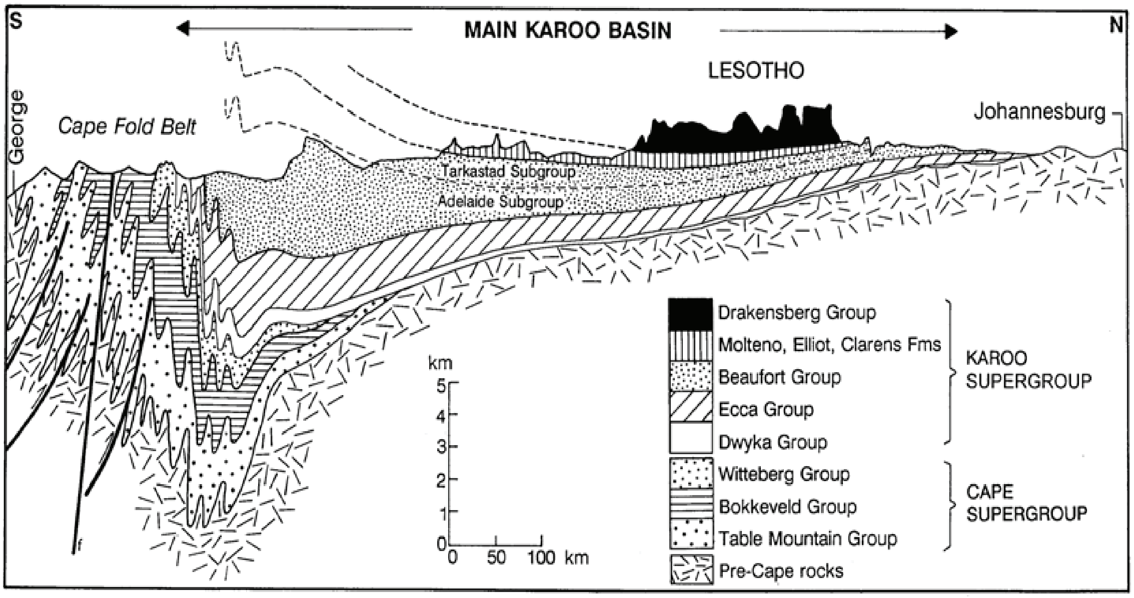


Figure 4: Cross-section of the Main Karoo Basin (Woodford and Chevallier, 2002).

2.2 Geology of the study area

The regional geology of Beaufort West is characterised predominantly by the Adelaide Subgroup of the Beaufort Group (CGS, 2005) (Figure 12). The Adelaide Subgroup (Late Permian age: 260 Ma) consists of the older Abrahamskraal and younger Teekloof Formations of alternating bluish-grey mudstone and grey very fine to medium grained sandstone (Chevalier et al., 2001) (Table 3). The Abrahamskraal Formation can be up to 2500 m thick whereas the Teekloof Formation can be up to 1400 m thick (Chevalier et al., 2001). The sandstone units were likely formed by lateral migration of meandering rivers, whereas the mudstone units were formed by deposition in a flood plain and lacustrine environment (Chevalier et al., 2001).

Jurassic age dolerite dykes and sills intruded into fractures of the Karoo sediments during a period of extensive magmatic activity across the entire Southern African subcontinent at the time of the Gondwanaland break-up (Chevalier et al., 2001). In the study area this resulted in a network of dolerite dykes, sills and even inclined sheets. The two main dykes are:

- The TBR-dyke (SRK 1997). An East-west trending dyke from the Nuweveld Mountains north of the Gamka Dam in an easterly direction cutting across the farms Tweeling, Brandwag and Renosterkop. This terminates into an interpreted dolerite ring structure on the farm Renosterkop.
- Another east-west trending dyke cutting through the town of Beaufort West.

There are also other dykes like the Droërivier dyke (SE-NW dyke north of Droërivier) and Hansrivier dyke (a small N-S dyke at Hansrivier). In addition, there are dolerite sills that cover the mountain tops as cap rock. The interpreted dolerite ring structure on the farm Renosterkop was described as a 'saucer-like inclined dolerite sheet' (Chevalier, 2001).

Table 3: Summary of the geology and relative age of rocks

Group	**Subgroup**	**Formation**	**Lithology**	**Age**
			Alluvium	Recent
			Calcrete and hard pan	Recent
Beaufort			Karoo Dolerite	Jurassic
	Adelaide	Teekloof	Mudstone and sandstone	Permian
		Abrahamskraal	Mudstone and sandstone	

A large part of the study area, especially in the lower lying areas, is covered by calcrete and hard pan deposits (CGS, 2005) possibly as a result of secondary weathering of the Karoo sediments. Alluvium covers the river valleys of the predominantly ephemeral streams.

Uranium mineralisation in the sandstone bodies of the Karoo Sequence near Beaufort West occurs as thin surface coatings onto the dark brown manganese oxide, locally called "koffieklip" (coffee rock) as shown in Figure 5. Since the early 1970s, this deposit has received much attention when uranium mining was intensified, with some research activities being commissioned by ESSO to assess uranium mining potential. For instance, a borehole (GZ00039), located on the farm called Ryst Kuil 351 about 45 km southeast of the Beaufort West town, was used for such a purpose. As the uranium can be released into the subsurface including the saturated zone under oxidised environment, it can become a source of contamination to groundwater resources and threaten a safe supply strategy heavily relying on local aquifers.

Figure 5: Example of the "koffieklip" on the farm Rystkuil, south east of Beaufort West (dark brown calcareous sandstone).

2.3 Regional hydrogeology

The outlines of the study area were determined by three factors:

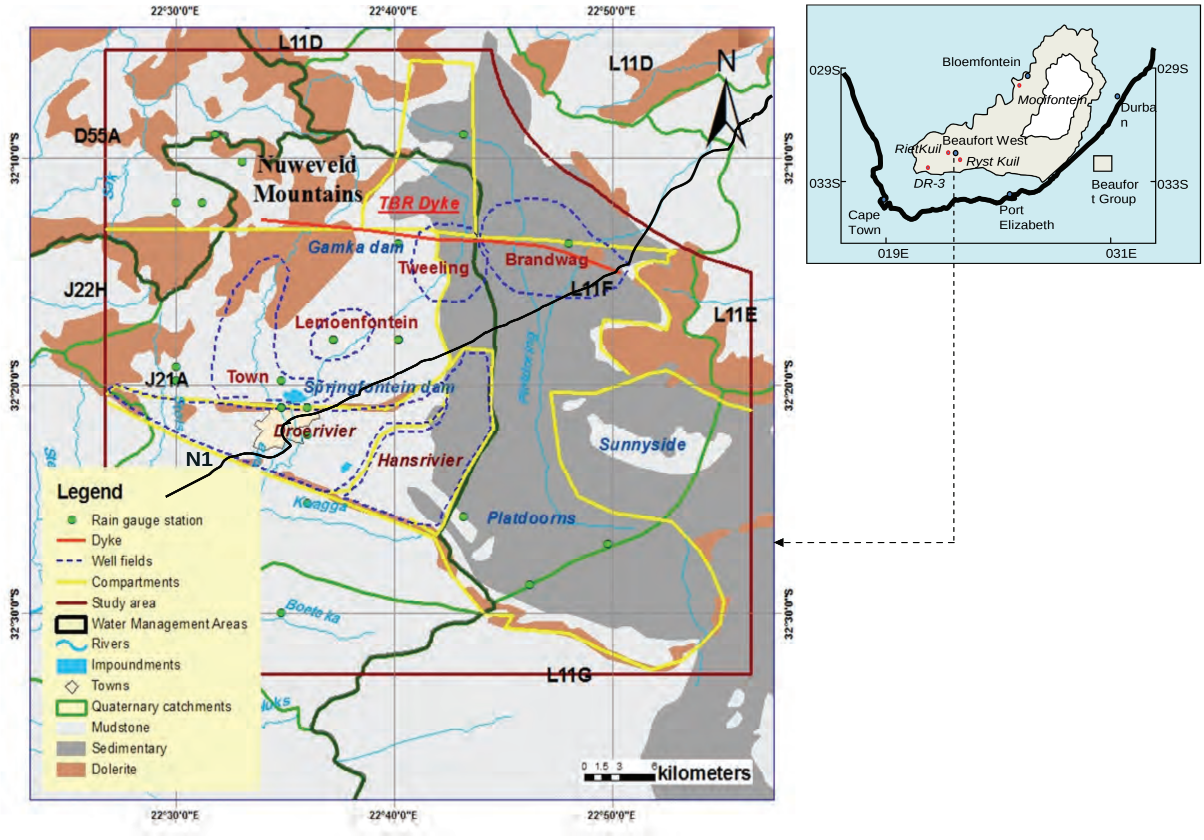


Figure 6: Locality of the study area.

1. Existing municipal wellfields (Townlands, Lemoenfontein, Tweeling and Brandwag) that have good data availability;
2. Potential groundwater development areas to the south to meet future water demand;
3. Uranium exploration and exploitation in the south and south-west from where no data could be obtained, but which might pose a threat to the water sources that are/will be exploited in future.

The study area as eventually defined (Figure 6) includes the town wellfields in the north and northeast (up to 40 km northeast of town), 40 km east of the town including the farm Sunnyside, 30 km south of the town up to the farm Blydskap.

The study area includes two surface catchments, (topography sheets J21a and J21b, and L11f and L11g) (Figure 5) and stretches over two Water Management Areas: Gouritz (primary catchment J) and Fish to Tsitsikamma (primary catchment L) (Middleton and Bailey, 2008). Local mean annual precipitation for the period 1972 to 2010 is 252 mm (Beaufort West municipal weather station). Local recharge was estimated at 2% of rainfall by Seward (1988). The GRA II report gives calculated mean recharge values of 1.76% (quaternary catchments J21A) and 2.315% (quaternary catchments L11F) of the total rainfall. This is equivalent to approximately 3.46 Mm^3 and 3.79 Mm^3 for these two quaternary catchments, respectively.

The hydrogeology of the area is determined by:

- The extensive alluvial cover on the bedrock that consists of mudstones, siltstones and sandstones of the Beaufort Group with very gentle amplitude folding, with dips rarely exceeding a few degree;
- Isolated dolerite intrusions, mainly dykes;
- Gentle slope in a southerly direction;
- Fracturing of the bed rock.

Fractured rock aquifers (secondary aquifers) cover most of the surface area around Beaufort West, although a combination of intergranular and fractured rock aquifers also exist as a result of alluvium and /or deeply weathered Beaufort sediments overlying the fresher Beaufort sediments (DWA, 2002). Generally the Beaufort Group sediments have low primary porosities, but the secondary porosity is well developed and is associated with weathering, minor folding, fracturing, faulting and jointing (Kotze and Rosewarne, 1997). High groundwater potential exists at the dolerite/sediment contact zones, the mudstone/sandstone contact zone, as well as in the fractured sandstone; especially where the proportion of mudstone to sandstone is small (SRK 1997). The alluvium in turn acts as storage reservoirs for recharged water from rain events and recharges the underlying formations (SRK, 1997). The fractured rock aquifer tends to produce higher yielding boreholes in excess of 5 ℓ/s, whereas those with dual porosities tend to produce boreholes with yields of between 0.1-0.5 ℓ/s.

2.4 Groundwater resources in Beaufort West

Current abstraction in the area serves the municipal and agricultural sectors. According to DWAF's water use registration database (WARMS), the groundwater consumption of the agricultural sector is 3.36 Mm^3/a for the J21A quaternary catchment alone. Registered groundwater use for L11F could not be sourced at the time of compiling this report.

Groundwater has played an increasingly important role in the town of Beaufort West (Figure 7). The importance of groundwater has increased from 50% in 1978 to 55% in 2007. As Gamka dam's capacity is limited and allocation of its supply to the town is around 0.5 Mm^3/a, a shortfall is imminent. The shortfall predicted (based on an annual population increase rate of 1%) can be seen in the right-most t part of Figure 7. It is therefore important for the town that additional wellfields be found. These will probably be located towards south east or west and far away from the town itself.

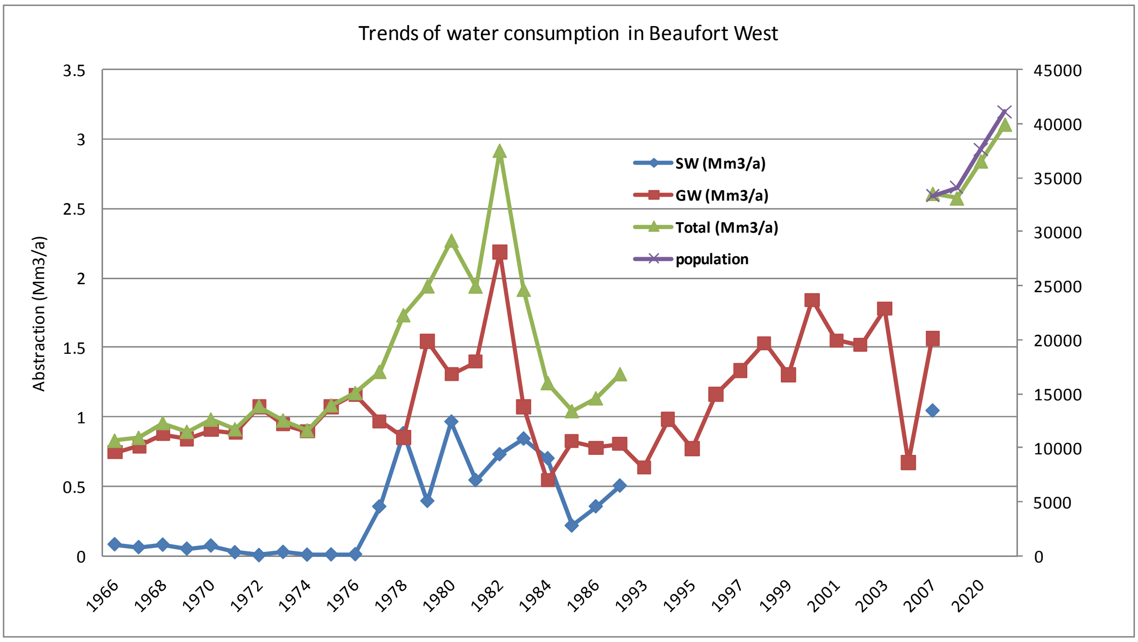


Figure 7: Trends of surface and groundwater resources in Beaufort West.

2.5 Previous work in Beaufort West

The discovery of uranium in the Beaufort West area in the early 1970s when the uranium price was at a high, has sparked a number of studies looking at uranium levels in the local environment. Moon (1974) reviewed information on the uraniferous deposits around Beaufort West. Uranium analyses of groundwater in the general area undertaken by the (then) Geological Survey, was reported by Beeson (1978), Marchant (1978), Murphy (1978) and Brunke (1977). Vogel et al. (1980) undertook a multi-parameter investigation of groundwater in the area north of the present study area, during which uranium isotopes, radium and radon was analysed. Scholtz (2003) studied ore spoils, soils and water on the farms Ryst Kuil, south of the present study area, where at that stage, mining had ceased. Tarras-Wahlberg (2008) reported on uranium analyses of five groundwater samples from the general Beaufort West area. No data are available from the areas occupied by various exploration companies that are quite active in the area (Uramin 2006, Brinkley 2007, Bohlweki 2008, Peninsula 2011).

The average crustal abundance of uranium is about 2 to 3 ppm. In the general Beaufort West area, levels in the sandstone and calcretes up to 2% (20 000 ppm) have been reported (Brunke 1977, Scholtz 2003). The uranium levels in groundwater of over 634 samples sampled by GS, form a log-normal distribution between 0.4 and 200 µg/L (geometric mean 15 µg/L) (Murphy 1978). As a very general rule, areas of high relief (typically along the escarpment northeast of the town) show low uranium levels in groundwater (U<6 µg/L; geometric mean 4.5 µg/L). Areas with low to gentle below escarpment have higher U values (U 6-30 µg/L; geometric mean 14 µg/L). Areas with low relief (Salt River, 35 km SE of Beaufort West) have high uranium contents (U>30 µg/L; geometric mean 40 µg/L) (Figure 8). Apart from this general pattern, there are a number of small 'anomalous areas' where groundwater uranium levels stand out amongst the general pattern around them (Figure 8). There is a good correlation between EC and U (Murphy 1978, Brunke 1977).

The anomalous high U levels do not necessarily indicate uranium ores. In fact, the object of the GS study was to investigate whether uranium in water would be a good prospecting tool. The conclusion was negative with the suggestion that molybdenum or radium (even though no radium was measured) could be a better tool (Brunke, 1977; Murphy, 1978).

Due to impact of droughts on local water security, hydrogeological investigations were conducted by the government and consultants including DWA (Seward, 1988), SRK (1997) and GEOSS (2006a).

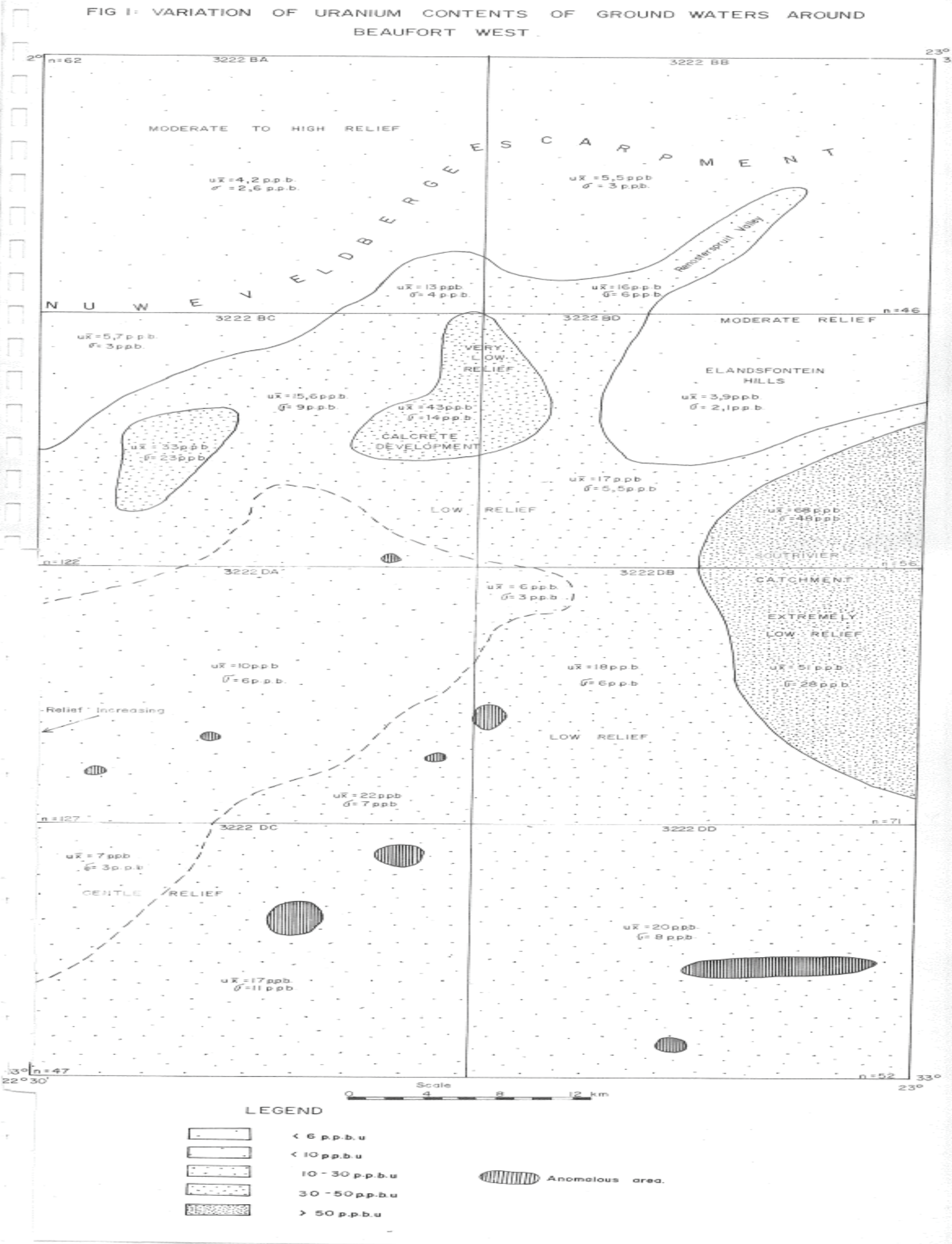


Figure 8: Variation of uranium content of ground water around Beaufort West (from Murphy, 1978).

3. BEAUFORT WEST FIELD WORK

3.1 Activities in Beaufort West

The field activities undertaken in the course of this project are:

- Hydrocensus undertaken by GEOSS (November 2006) to obtain borehole data and to sample for chemistry and stable isotopes;
- Hydrocensus trips undertaken by UWC staff (May 2008 and June 2009) to obtain borehole data and to sample for chemistry and radionuclides;
- Pumping and tracer tests carried out in 2010;
- Further field visit by UWC staff in May 2011.

On all of these occasions discussions were held with various stakeholders (authorities, farmers) from whom their needs were established and local information was obtained.

3.2 Aquifer properties

Pumping test data were acquired from a variety of sources to compile a regional map of transmissivity and storativity. The sources include historical reports (DWAF and SRK Consulting), the NGDB now NGA, as well as the recent pump tests conducted by GEOSS. The spatial distribution of transmissivity and storativity are also reported. The data is limited mainly to the municipal well field areas, which reflects the areas most extensively explored over the past 20 or so years. The transmissivity and storativity values represent the average horizontal transmissivity and storativity values at the respective localities.

Generally there is a strong correlation between borehole yields and transmissivities. Areas with high transmissivities > 100 m^2/day are generally associated with borehole yields greater than 5 ℓ/s. Transmissivities between 10-100 m^2/day are associated with borehole yields between 2-5 ℓ/s whilst transmissivities < 10 m^2/day are associated with borehole yields < 2 ℓ/s.

Table 4: Summary of T & S in the study area.

Subarea	**Transmissivity (m^2/day)**	**Storativity dimensionless**
Brandwag east	>200	0.01-0.001
Brandwag west	<200	0.0001-0.00001
De Hoop	30-300	0.001-0.00001
Platdoorns	<10->200	0.00001
Lemoenfontein	100-250	0.0001-0.00001
Town well	40->400	0.001-0.0001
Droerivier	<10	0.001-0.0001
Hansrivier	>300	0.001-0.0001
Sunnyside	100-360	0.00001-0.000001

No clear correlation is visible between the observed transmissivity values and the geology. This may be due to heterogeneity of terrestrial sedimentary facies dominated in Karoo Group. A general field observation is that boreholes drilled on the dolerite contact zones are higher yielding than those drilled in the sediments of the Teekloof formation. A case in point is two boreholes drilled on the farm Hansrivier on the contact of a dolerite dyke that produced sustainable borehole yields in excess of 10 ℓ/s. Although the latter observed transmissivities were well in excess of 300 m^2/day, it is no different to other areas in the municipal well fields (Town and Brandwag well fields) associated with the fractured sediments of Teekloof formation in the absence of any dolerite dykes. Hence it seems as if the degree of fracturing is more important than the lithology, although the mode of emplacement of the dolerite dykes seem to control the degree of fracturing within the host rock (Teekloof formation) (Chevalier et al., 2001).

3.3 Tracer experiment

A forced-gradient tracer test was conducted to test and verify the key aquifer properties (van Wyk, 2010). On the 10-02-2010 a tracer experiment under radially convergent flow conditions (pumping) was conducted to obtain more constrained aquifer parameters of the area surrounding the dolerite dyke on the farm Hansrivier, Beaufort West. The boreholes utilised for the tracer test were HR.10 (pumping) and G29936HB (injection) situated at a distance of 42 m from each other. The experiment consisted of two components i.e. a tracer dilution in the injection borehole using non-iodated salt (NaCl) followed by the addition of the fluorescent dye uranin ($C_{20}H_{10}Na_2O_5$) and recovering it from HR.10. The salt injection process was carried out as a trial run before the actual tracer test with uranin in order to optimise the sampling schedule. 20 g of uranin was dissolved in 500 ml of site water and injected using a low flow pump into borehole G29936HB with 5 ℓ of chase fluid, once the drawdown stabilised (linear gradient).The injection process lasted less than 4 minutes, which can be assumed to be instantaneous with respect to the mean residence time of the tracer (~366 minutes).After the tracer (Dirac pulse) was injected, the borehole column was mixed using a slug/bailer in order for the entire borehole section to be uniform with respect to the tracer solution, thus allowing the tracer to flow in fracture zones to the abstraction borehole (HR.10). The volume of both the tracer and chase fluid were reduced to the smallest possible amount in order to minimise the initial spreading of the tracer plume around the injection borehole. A spectroflourimeter was installed above the pump and was used to measure the uranin concentration at 2 min intervals. Following the surprisingly fast arrival of the uranin (indicating good fracture connectivity between the boreholes), the sampling interval was reduced to 10 s.

The Single Fissure Dispersion Model (SFDM) developed by Maloszewski and implemented in the software Traci95 was used to fit the observed BTC (Käss, 1998). The Traci95 software program was also used for modelling the tracer breakthrough curves and determining the hydraulic properties of the main and secondary flow paths. The theoretical tracer breakthrough curves were simulated using the best-fit method on the basis of measured concentrations. The parameters of the SFDM obtained by fitting Eq.1 to the tracer concentration measured at HR.10 are summarised in Table 5. The tracer test using uranin during the project revealed that effective porosities of the fractured rock aquifer near Hansrivier dyke range from 4% to 8.69%, orders of magnitudes difference from those documented in Table 2 (Van Wyk, 2010). Other parameters calculated by applying the SFMD were longitudinal dispersivity, fracture aperture and the mean flow velocity.

Table 5: Fitting Parameters of the SFDM (Pe, t0, and a) and derived physical parameters (2b, ∝l, Deff, nf, and v).

Uranin		Main flow path	Flowpath.1	Flowpath.2
Pe	[-]	0.88	6556	3152
t_o	[s]	22003	29027	47706
A	[s^$^{-0.5]}$	0.00097	0.00046	0.00039
2b	[µm]	828	721	563
α_l	[m]	47.5	0.0064	0.0133
Deff	[m^2/s]	6.46E-12	1.10E-12	4.82E-13
Nf	[%]	4.01	5.29	8.69
V	[m/s]	1.90E-03	1.44E-03	8.76E-04

3.4 Borehole profile at Olive farm

Hydrochemical profiling of boreholes can provide information on the inflow(s) into a borehole and therefore determine the need for purging prior to sampling. Borehole Olive2 (with co-ordinates: S 32.504900 and E 22.565220) was tested on May 12, 2011 on the farm Lombardskraal (~20 km Southwest of Beaufort West). The borehole was installed with a normal pump at the depth of 70 mbgl (static water level was 7.61 mbgl). An YSI meter which recorded temperature, pH and EC variations with depth in a water column was used.

The first profile was run on the undisturbed water column (Figure 9). The borehole was then pumped from a depth of 70 mbgl at a rate of 0.8l/s for about 5 hours, whilst continuously measuring pH, temp and EC. Thereafter the second profile was run (Figure 9).

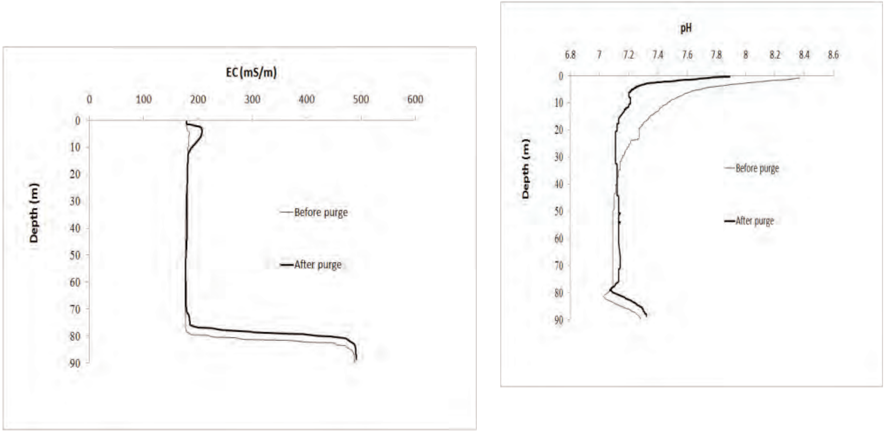


Figure 9: Comparison of EC (uS/cm) and pH profiles before and after purging.

The logging information from this borehole displays an active flow system on top, indicating low mineralised recently recharged water with more evolved highly mineralised/stagnant water occurring at the bottom of the borehole. EC and pH is uniform from about 20 to 80m, whereby there is a sudden significant jump in the electrical conductivity at about 80 m depth. This might indicate a change in lithology or it could also be due to density fluctuations within the borehole column causing a pronounced stratification. The same borehole was logged in 2009 and shows almost an identical profile as to the one above. But this may not lead to the conclusion that the purging would not have a significant influence on the overall profiles. Monitoring for uranium radioactivity in such a borehole may proceed with purging process as the loss of CO_2 while the water is standing may result in a higher pH causing loss of uranium.

3.5 Recharge localisation

To verify local recharge estimates, a RIB model was applied to water level measurements taken in a borehole (G29946b) in the Gamka wellfield north of the town. Assumption were an area of 100 km^2, a recharge rate of 0.5% was independently obtained assuming that Sy (specific yields) is 0.002, with timelag of 2 months behind the relevant 24 months rain events (Figure 10). The study area covers the majority of these two quaternary catchments (J21A and L11F). The groundwater recharge over the study area is spatially variable. Higher recharge (> 10 mm/a) is expected in the north along the Nuweveld Mountain, whilst there is a gradual decrease towards the south and southwest. The groundwater recharge is a minimum in the southwest where < 1 mm/a is expected (DWAF, 2005).

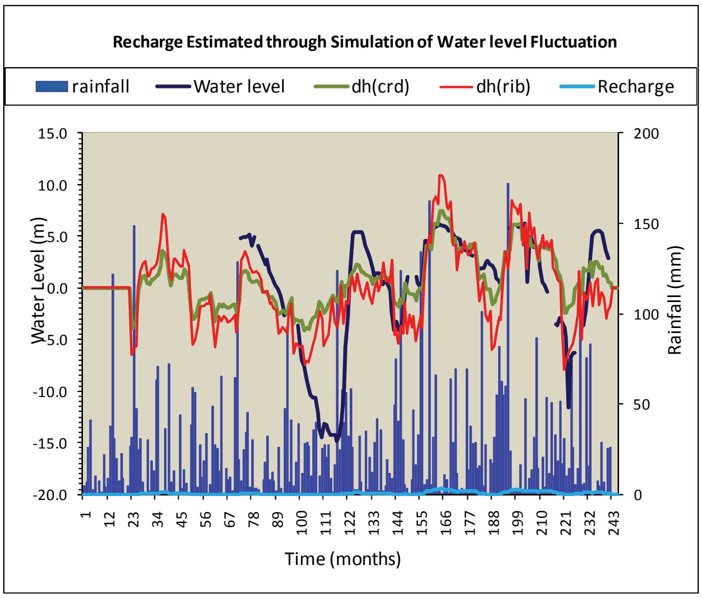


Figure 10: Recharge estimate for the Gamka wellfield using a RIBs model.

4. BEAUFORT WEST HYDROCHEMISTRY

4.1 Access to existing information

The nature of the project allowed for the research team to make use of a wealth of existing information consisting of papers, reports, conference presentations and other documents that were obtained from their host institutes or from online searches. Field investigation and verification still remain important approaches to direct the project objectives.

All existing data and information were collected and collated into Excel spreadsheets. The data were derived from a variety of sources. These sources include the following major investigations:

- DWAF study in the Beaufort West area in late 1970s (Campbell, 1980).
- Salt River (Bureau de Recherches Geologiques et Minierer (BRGM) (1979).
- Nelspoort (Leskiewiez, 1997).
- A re-evaluation of the geohydrology of the area by DWAF (Seward 1988)
- A private Excel-based database of Mr. Piet Havenga of DWAF.
- Technical reports by consultants (SRK, 1997, 1998; GEOSS, 2005, 2006a, 2006b, 2006c, 2007a, 2007b, 2007c, 2007d, 2008).
- New boreholes recently drilled for the Beaufort West municipality by GEOSS.
- Hydrocensus information of GEOSS conducted in November 2006 (GEOSS, 2007a).
- Hydrocensus information of UWC conducted in May 2008 and June 2009.
- Field visit by UWC in May 2011.

The collated database in this report includes water levels, water chemistry (i.e. major anions, cations, trace elements, EC, pH, stable isotopes), borehole yields (i.e. blow yields and tested yields), transmissivity (T) and storativity (S). Where possible the data were checked for correctness and updated where required. Small seminars were also held between the team members from the different organisations involved.

4.2 Hydrochemistry

Water chemistry information (macrochemistry, stable isotope and radionuclides) was included in the database (see appendix A and B). The macrochemical time series data is provided in Table 9 in Appendix B. EC values were captured into the database.

To depict hydrogeochemical features of local aquifers, an expanded Durov diagram of sampled groundwater was constructed as shown in Figure 11. Major pattern of hydrogeochemistry is characterised by dominance of CaMg-HCO_3 and Mg-SO_4. Occasionally evidence of groundwater contamination was obvious. Overall the pattern is that of fresh water below the escarpment while highly mineralised water is found in areas of low relief where discharge predominates. This observation is confirmed by the indicator of EC.

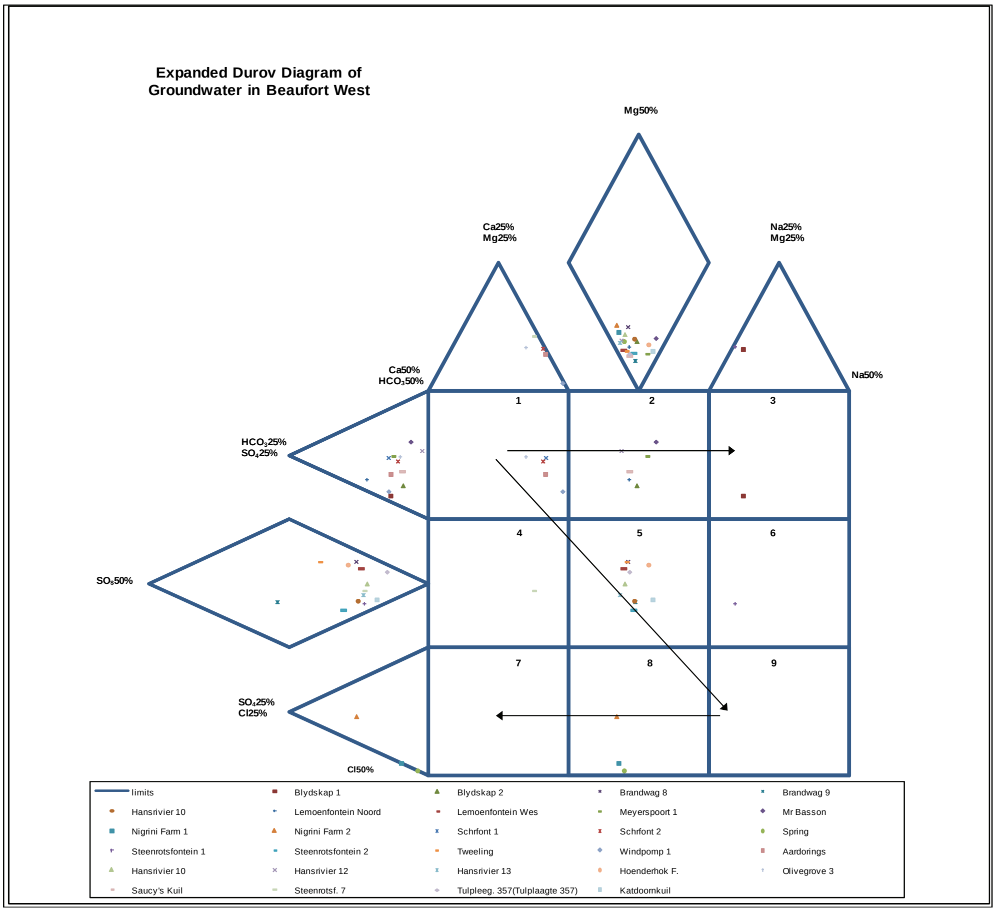


Figure 11: An expanded Durov classification of Beaufort West aquifers.

As showed in Figure 12, a general increase in EC from northwest to southeast over the study area. The lower ECs (0-150 mS/m) in the north coincide with the Nuweveld Mountains which represent the main recharge area. An elevated EC zone is observed in the centre of the area where the EC reaches a maximum (i.e. > 520 mS/m) about 15 km east of Beaufort West town, as well as in the eastern part of Brandwag wellfield. The former area is a narrow strip that stretches southwards from the N1 highway to the R61 (Beaufort West to Aberdeen). This area also coincides with an area associated with surficial calcrete deposits. There seems a general correlation between the elevated EC and calcrete deposits. The area east of Brandwag is associated with an area that is currently being heavily exploited, both for municipal and agricultural purposes. This area is characterised by slow recharge and large distance from the recharge area along the TBR Dyke. In the far eastern part of the map (Sunnyside Farm) an area of lower ECs (< 150 mS/m) is observed, which might further suggest a local recharge area with a westerly groundwater flow component.

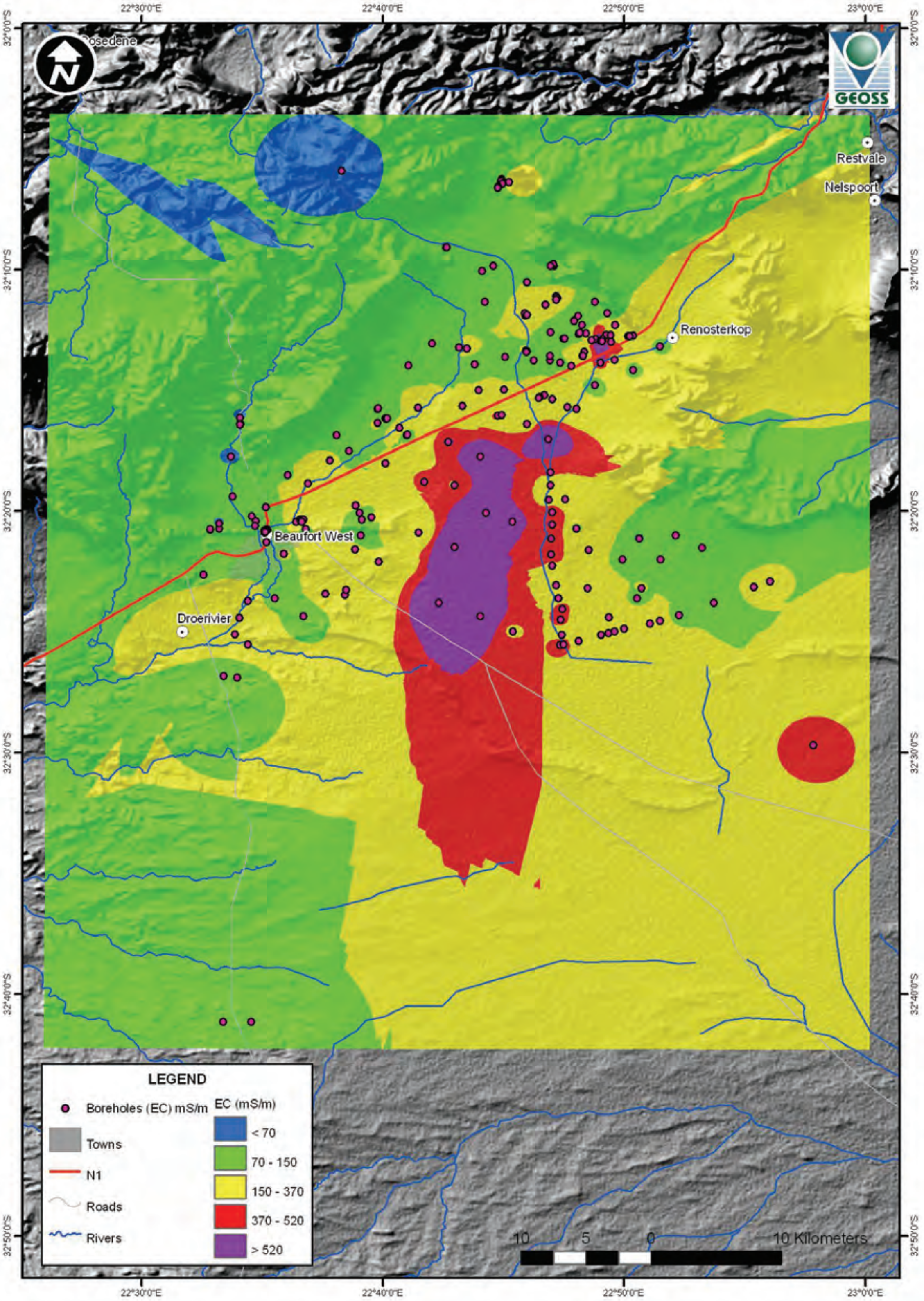


Figure 12: EC contour map.

In terms of drinking water standards, EC can be used as a proxy indicator for groundwater quality. Based on Figures 11 and 12 and Table 5, the majority of samples reflect a good quality for drinking and domestic purposes. A rough water quality classification could be made based on the 300 mS/m cut-off value (above which there is a "probability of disturbance of the body's salt balance" DWAF 1996). According to this classification:

- groundwater in the Gamka, Lemoenfontein and Hansriver wellfields is of acceptable quality;
- groundwater in the Brandwag wellfield is generally acceptable, with the exception of the boreholes south of the national road where the water is of marginal quality;
- groundwater from the Klipkraal, Montana and Kamferskraal is of marginal quality;
- Groundwater from the Salt River area is unacceptable.

There is no unequivocal evidence to support anthropogenic contamination in the municipal wellfields.

Table 6: Electrical conductivity trends for selected boreholes

BH number	**EC (mS/m)**				
(mapsheet)	1975-76	Feb/Mar-1988	1996-97	Nov-06	May-08
G29877U (3222bd70)	160	433			
G29877B (3221cb2)	160	433			
G33542 (3222bb97)	-	149	154		
G33544 (3222bb94)	-	67	90		
G29872d (3222bb302)	120	155	160		
G29940b (3222bb15)	280	114			
G29899f (3222bb23)	123	152			
G29896k (3222bb28)	104	109	144		
G29858b (no.8)(3222bb17)	82	80	82	134	117
G29857f	152	89			
G29859g	91	86			
G29859d (3222bb301)	105	127			
G29913r (3222bb25)	96	134			
G29977q (3222bd78)	178	197			
G29941p (3222bd79)	292	606			
G29941i (3222bd80)	241	626			
G29914a (3222bb241)	280	71	84		
Note: updated after Seward (1988)					

The EC trend was reasonably stable at most boreholes over the past ten years, though larger variations were found when data from the 1970s and 1980s are considered (Table 6). The notable exceptions are G29858V (No.9) and G29858B (No.8) in the Brandwag wellfield. In the case of G29858V (No.9) the EC increased by 149 mS/m, from 126 mS/m in June 1997 to 275 mS/m in November 2006[§]. The EC at G29858B (No.8) increased steadily from 82 mS/m in 1996 to 134 mS/m in November 2006 (Table 6). However, it must be stressed that such large increases in EC does not apply to the entire Brandwag well field, and appear to be very localized. At Private 2 (No.12) the EC decreased substantially from 270 mS/m in 1997 to 215 mS/m in

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[§] Note the 1997 sampling was carried out in June and the 2006 sampling was carried out in April and November, so exact seasonal comparisons cannot be made.

November 2006, whilst the ECs at G29858KA (No.1), G29894L (No.2) and G29859C (No.6) revealed minor increases or decreases (< 10 mS/m) over the past 10 years. A more careful investigation of the areas in which these variations occur, might be useful for the municipality to predict future water quality in the wellfields.

4.3 Stable isotopes

The stable isotope data set from the study area consists of a set of samples collected by GEOSS in 2006 during the first hydrocensus and those of Vogel et al. (1980) from an area to the north of Beaufort West towards the Nuweveld Mountains and 25 km to the east. The ^{18}O-deuterium plot follows a fairly straight line from the intersection with the Global Meteoric Water line (δD = 8*δ18O + 10 ‰) with a slope of 6.3 (Figure 13). This line is characteristic of rainfall in the area. Van Wyk (2010) recently reported a Local Meteoric Water line, also below the GMWL with slope 5.3 for Beaufort West rainfall.

Two groups are evident in the groundwater (Figure 13):

- A group of samples at the end of the LMWL with δ18O between -2.3 and +0.1 ‰. These samples are from boreholes all located within a radius of 1 km on the edge of Beaufort West town near the Springfontein Dam. Such enriched evaporative signatures in these boreholes give rise to suggestion that they are influenced by the residual dam water. Perhaps it would be a good idea to also sample the Gamka dam and see where it plots relative the GMWL.
- A group with low δ^{18}O (between -6 and -4.5 ‰) more or less along the GMWL. This group is represented by samples from all areas other than the Townlands group. The samples reported by Vogel et al. (1980) all had δ^{18}O similarly between -6 and -4.5 ‰ for other parts of the present study area.

It seems reasonable to conclude that the Townlands group of boreholes is recharged by a different water source than those elsewhere in the area. This source is likely to be river water brought down towards the town during periods of heavy flooding or from the dam. The groundwater samples from outside the townland are isotopically more depleted than the groundwater from groundwater within the townland. This pattern has to be related to difference in altitude of the recharge areas.

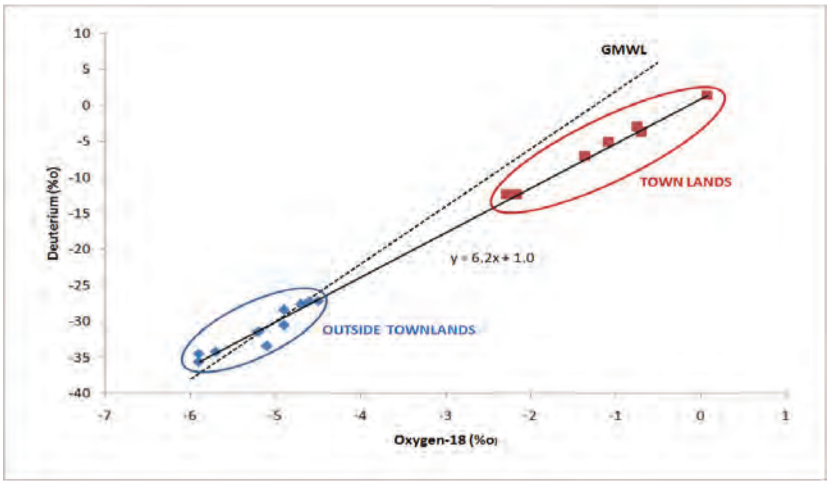


Figure 13: δD-δ18O plot of groundwater samples collected in 2006.

4.4 Radioactivity

Consideration was initially given to the use of gross alpha and beta measurements to estimate the dose contributions from all radionuclides. The uncertainties inherent in the determination of gross alpha and beta activity (typically 25%) lead to unacceptably large uncertainties in the final dose determinations and were thus not used in this case. It was also considered useful to obtain data from a wider range of radionuclides.

Dose rates of all the samples were calculated and evaluated in terms of the South African radioactive water quality guidelines for domestic use (DWAF 2002) Table 1. It can be seen that most of the samples fall in Class I (< 0.1mSv/a, indicating good water quality) with the exception of one sample (Steenrotsfontein 2) falling in Class II (0.1-0.250 mSv/a for the less than one year age group) with marginal water quality and therefore does not pose an immediate risk to people using borehole water for consumption.

The raw data of sampling results collected during this project can be found in (Appendices C). The fact that all the samples, with one exception, are within the acceptable range as specified above, implies that the radioactivity in groundwater is controlled more by the hydrological and lithological settings. This would make sense as past mining activities focused on specific areas, especially to the east and northwest of Beaufort West. No physical data access was allowed on those areas that are currently being prospected for uranium. The extent and depth of the uranium ore body is also not known due to the mines and their consultants treating all this information confidential.

As reflected in appendix C, no evidence of uranium contamination was established in any of the boreholes sampled during this project. A contour map of radioactivity in groundwater surveyed is shown in Figure 14.

However, it appears from water quality data of the underlying aquifer that the Beaufort West Waste Water Treatment Works (WWTW) might contaminate the aquifer, which is part of the municipal water supply sources. This needs to be addressed in the upgrading of the WWTW. Improved monitoring and metering of treated sewage effluent is also required.

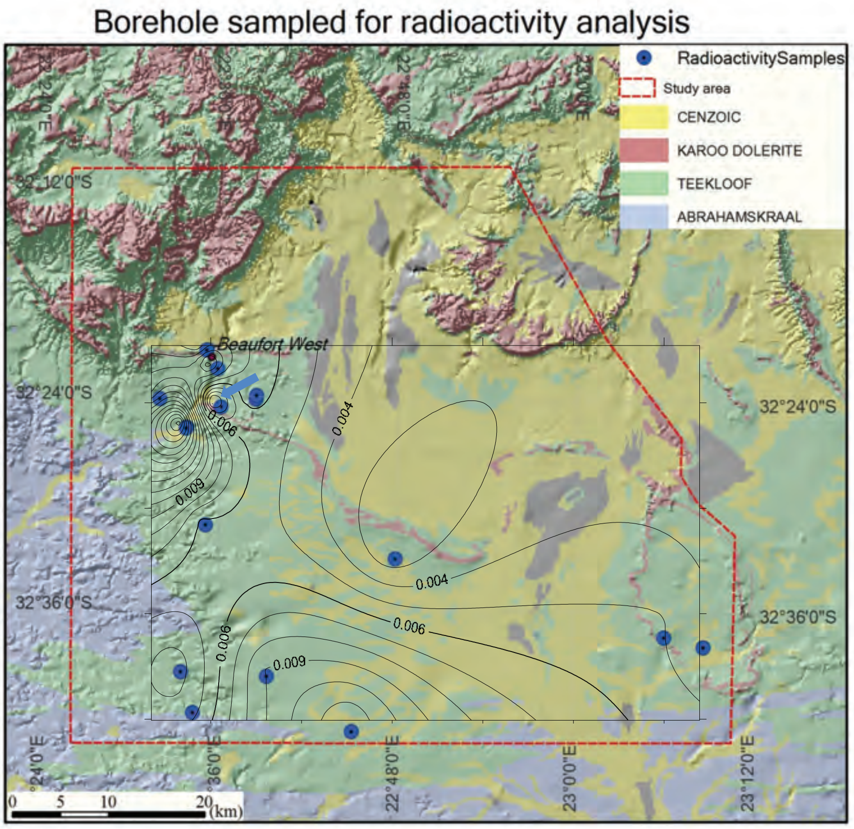


Figure 14: A contour map of radioactivity of U^{238} in groundwater (mSv/a) in Beaufort West.

4.5 Conceptual flow model

The interpretation of the chemistry results contributed significantly towards the development of a conceptual model over an area from north to south through Beaufort West town (Figure 15). Spatial information of boreholes, topography and geology (available borehole logs) were used in conjunction with the chemistry data to compile the conceptual model.

The analysis of the isotope data showed 2 isotopically different water types (Figure 15). The Beaufort West spring is likely to be structurally controlled by the Town Dyke that is outcropping along a prominent east-west ridge that trends through the northern parts of the town. The Town Dyke is relatively steeply inclined towards the north. Hence, the Beaufort West spring discharges water that is likely to be related to dominant shallow surface water, which might be geochemically influenced by tenuous deeper regional flow system dominated by connate water. Although the latter is not consistent with the macro-chemistry, it is anticipated that there is some water-rock interaction taking place. This needs to be further investigated.

The groundwater at Brandwag, Tweeling, Lemoenfontein and upper Town well field also taps the upper shallow groundwater system associated with the fractured sandstone, siltstone and mudstone. However, these boreholes are not linked to the deeper groundwater system as they are topographically much higher and further away from the Beaufort West spring.

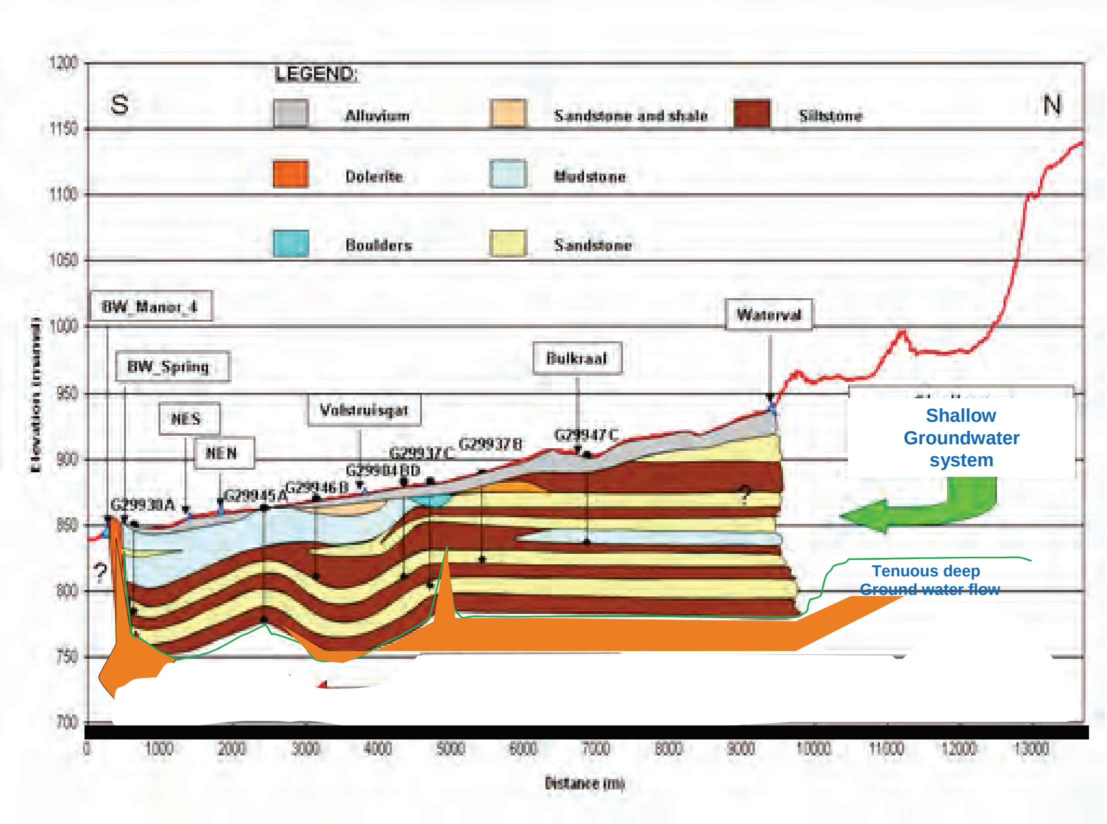


Figure 15: A sketch showing a conceptual hydrogeological cross-section.

5. WATER SUPPLY SECURITY

5.1 Basic approach

The implementation of aquifer protection zoning has long been practised in developed countries like the US and Europe, however its local adoption in South Africa has not been easy as a result of the developing nature of socio-economic infrastructures (Xu and Braune, 2010). Moreover, the delineation of protection zones in fractured aquifers is a challenging task due to the heterogeneity and anisotropy of hydraulic conductivities, which makes prediction of groundwater flow organisation and flow velocities difficult (Berkowitz, 2002). The idea behind source protection areas (SPAs) also known as zones (SPZs), is to defend the aquifer against degradable contaminants, in which case subsurface residence time appears to be the best measure of protection, and against non-degradable contaminants where flow path dependant dilution must be identified. Pochon et al., (2008) points out that both are needed to provide a comprehensive and practical definition of protection zoning.

5.2 Concept of safe distance

This applies to a zone that should provide a minimum safe distance which separates a water resource from a potential contaminant source. The concept of travel times and minimum safe distances is more apt to biodegradable contaminants than the non-biodegradable. A minimum safe distance is that horizontal distance which safely separates a water resource and a potential contaminant source. This distance ensures that the time taken for the horizontal travel of the contaminant is sufficient to allow physical and biochemical degradation of the contaminant. For bacteria and viruses a travel time of 30 days and a minimum distance ranging between 15-50m (depending on aquifer conditions) has been proposed for South African conditions. Distances are calculated using a modification of Darcy's Law (Xu and Braune, 1995). The concept of safe distance has for all intents and purposes been adapted to South African conditions in an attempt to deal with the negative impact of pit latrines on groundwater quality particularly in rural areas (Xu and Braune, 2010). The National Department of Water affairs and Forestry in South Africa developed a technical guideline (Xu and Braune, 1995), which provides rule of thumb estimates of the safe distance. Typical minimum distances of between 10m and 50m are prescribed between water point and latrine. Implicit within the guideline are three factors that dictate the optimum separation between latrine and water point: the depth to water table, the composition of the soil and the characteristics of the aquifer. Where hydrogeological conditions are known a priori to water professionals, a simple calculation can be used to estimate the minimum distance (Xu and Braune, 1995). Actual values of the separation distance to be used for specific sites depend on such parameters as aquifer thickness, porosity, hydraulic gradient, average pumping rate and duration.

5.3 *Zoning approach*

Contamination of groundwater sources has been observed world-wide, and it is becoming self-evident that concentrated human activity will lead to even more groundwater contamination. In general it has been shown that contamination of drinking water occurs where three main components exist:

1) A potential source of contamination,
2) An underlying aquifer and
3) A pathway for transfer between the two.

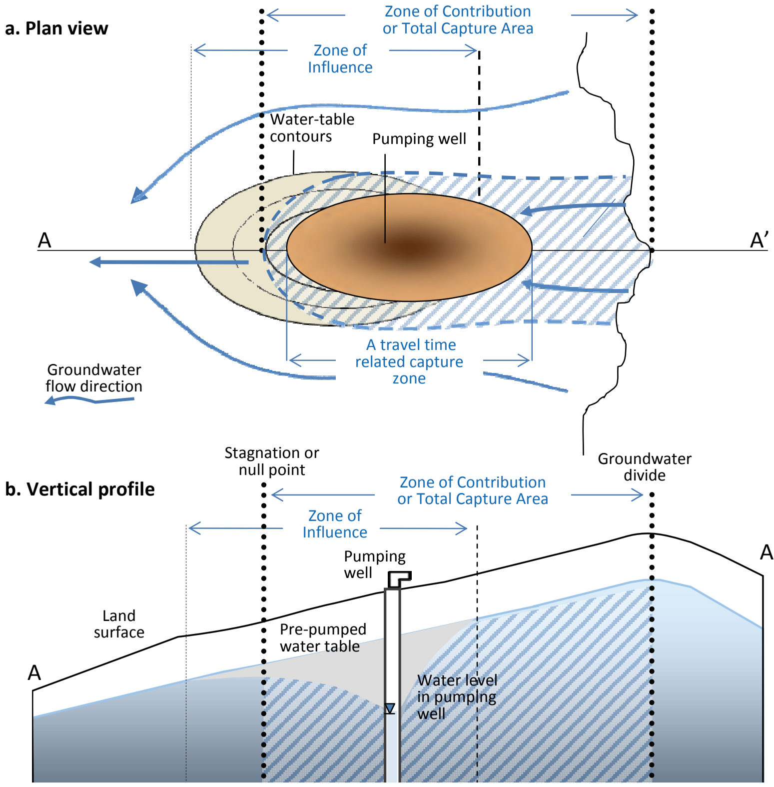


Figure 16: A sketch illustrating basic concept of a wellhead protection area with both plan view in (a) and cross section in (b) (after US EPA, 1987).

Groundwater contamination is a major issue particularly in rural areas of South Africa. One of the ways of protecting this resource is by using a zoning approach. Aquifer protection zoning also called wellhead protection or more locally known as borehole protection zoning is used to delineate a capture zone or zone of contribution for a specific well (borehole). In the simple porous-media flow system illustrated in Figure 16 the WHPA is a symmetrical area extending from just downgradient of the well to an upgradient groundwater divide. The delineation of a wellhead protection zone is the process of determining what land or geographic area should be included in a protection zone program. Commonly, zones or areas are delineated to achieve the following levels of protection (Nel et al., 2009; Xu and Braune, 2010):

- A Wellhead Operational Zone immediately adjacent to the site of the borehole or wellfield to prevent rapid ingress of contaminants or damage to the borehole (also referred to as the Accident Prevention Zone).

- An Inner Protection Zone based on the time expected to be needed for a reduction in pathogen presence to an acceptable level (often referred to as the Microbial Protection Area).

- An Outer Protection Zone based on the time expected to be needed for dilution and effective attenuation of slowly degrading substances to an acceptable level. A further consideration in the delineation of this zone is sometimes also the time needed to identify and implement remedial intervention for persistent contaminants.

- A further, much larger zone sometimes covers the total catchment area of a particular abstraction where all water will eventually reach the abstraction point. This is designed to avoid long term degradation of quality.

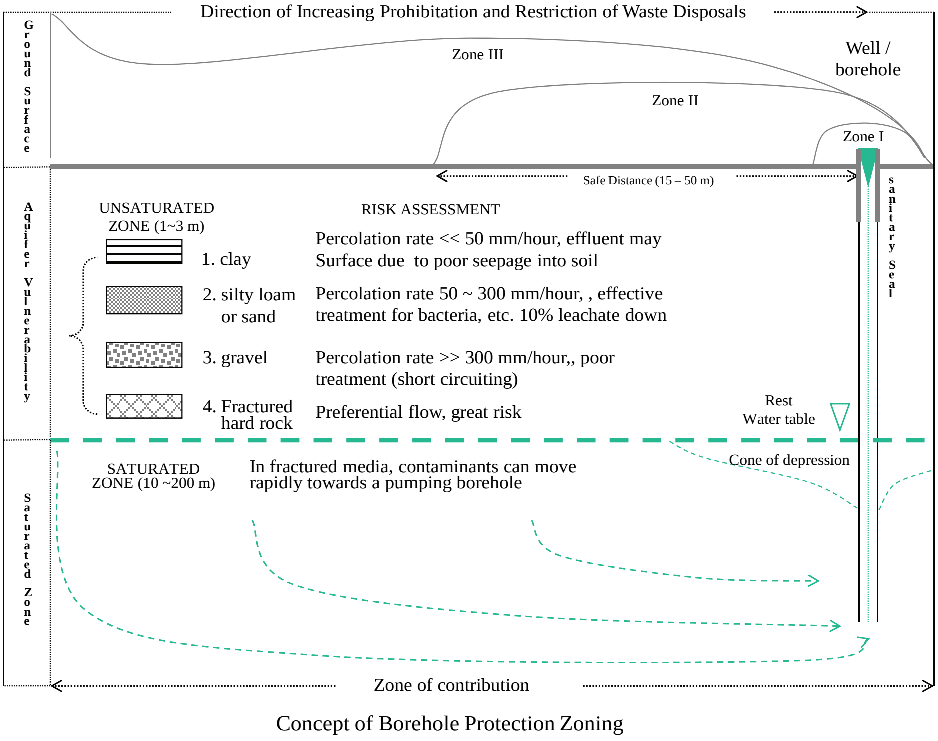


Figure 17: A conceptual cross-section of protection zones around a borehole.

In terms of hydrogeological cross section, a conceptual diagram can be presented in Figure 17. As seen in Figure 17, passage of potential contaminants through the unsaturated zone is critical to attenuation process.

The approaches used to delineate protection zones range from relatively simple methods, based on fixed distance, through more complex methods, based on travel times and aquifer characteristics, to sophisticated modelling using log reduction models and contaminant kinetics (Nel, 2010). Internationally a wide variety of techniques has been recognised to determine protection zones ranging from very simple non-analytical methods to complex numerical transport models (US-EPA, 1993). The choice of delineation technique will also be a function of (Foster et al., 2006):

- The degree of understanding of the government setting involved,
- The operational importance of the groundwater setting concerned,
- The human and financial resources available.

6. SUSTAINABILITY OF GROUNDWATER UTILISATION

Adaptation of groundwater protection methods is highly dependent on local geological formation, aquifer properties, groundwater occurrences, type of prevailing contaminants and purpose of groundwater utilization. As hydrogeological conditions are discussed previously, the focus here is placed on sources of contamination and natural geological attenuation processes in the region.

Beaufort West is essentially a rural town. In addition to a tourist attraction, it maintains livelihoods for local rural communities. As no evidence of uranium contamination was present in any of the boreholes sampled during this project, sources of contamination in this rural environ include cattle kraals, feeding lots, lucern farming, highway spillage and modest waste disposals. As many wellfields are located near the town or along the main National Road (N1), the sources are expected to be municipal disposals, informal dumpings. It is also reported that the leakage of filling station presented a problem for groundwater contamination.

Groundwater quality is generally acceptable except for hotspots of nitrate and stratification of chemistry in aquifer. It is noted that high concentration of nitrate are limited within dyke-bounded compartments. Although the natural attenuation capacity in fractured rock aquifers is limited, impermeable dykes serve as a solid blockage for migration of bad quality water over the compartments.

Due to the nature of semi-arid climate in the Beaufort West, another possible pass for contaminants to gain access to water source points is storm water during flooding times. Although such a possibility is there, ferocious droughts still prevail over past decades, causing severe shortage of water supplies in both town and rural farming communities in the area.

To effectively protect valuable groundwater resources in Beaufort West, a conceptual model should be considered for implementation of protection best practice or measures including zoning approach.

6.1 Groundwater flow regime

The available water level information was used to produce a water level contour map for the delineation of groundwater flow paths over the study area. About 200 boreholes have water level information. These points were used to contour the groundwater levels on a regional (coarse) and local scale (detailed). At each point the most recent measured water level was used for interpolation.

A regional-scale groundwater flow regime is considered. The regional groundwater flow pattern is generally from north to south. The piezometric heads vary from > 1500 mamsl in the north coinciding with the Nuweveld Mountains to about 800 mamsl in the south coinciding with the flat lying plains. Note that only 4 points were sourced with piezometric head information above 1300 mamsl – these points are all situated in the mountainous areas in the north. However, the spatial distribution of the boreholes in the flatter area is sufficient to confirm the regional groundwater flow paths from north to south.

A local scale groundwater contour map was also produced using the interpolation software, i.e. Tripol. Tripol is an interpolation program that estimates values for random variables from a given set of regionalised variables. Tripol includes the following:

1) Computation of a semi-variogram for a set of data points.
2) Fitting of a mathematical function to the semi-variogram
3) Estimation of values for any set of random data from the given set of data points.

Tripol implements 3 interpolation methods, i.e. Distance Weighting, Kriging and Bayesian Estimates. Kriging and Bayesian Estimates do not only yield an estimate of the random variable, but also an error in the estimate. For Kriging and Bayesian Estimation, a semi-variogram is required to estimate the manner in which the mean values of the known dataset behave over the region. A mathematical function is then fitted to the semi-variogram values to obtain certain parameters that are needed for the interpolation by Kriging and Bayesian Estimation. The same 200 boreholes (used for the regional contour map) with groundwater level data were again used for the Tripol software program together with over 5000 unknown points for the interpolation. The applicability of the Bayesian Estimation technique was tested prior to conducting the interpolation method. The available water levels within the grid were plotted in graph format against the elevation (topography). A correlation of about 99% (R^2) was obtained, which implied that the technique is definitely applicable. Utilising the Bayesian estimation technique within the Tripol software, the mathematical function used to fit the semi-variogram produced a correlation coefficient of about 80.6%. At the end of the interpolation Tripol provided the solution in a grid format that was imported into the Surfer 8.0 software package for contouring purposes.

A contour map (Figure 18) with contour intervals of 5 m was then produced as well as a groundwater flow net that provides the direction of groundwater flow in the area (Figure 19).

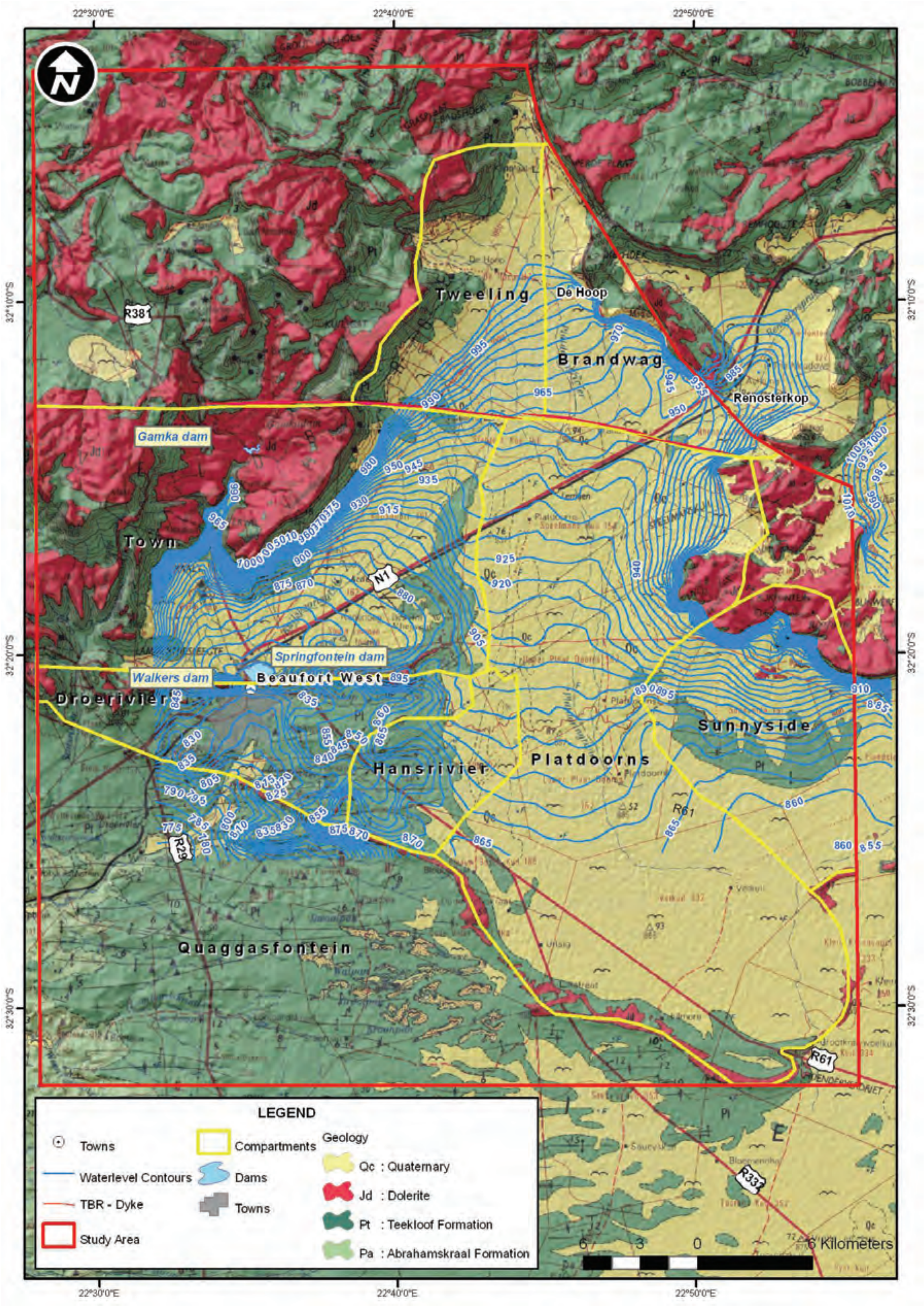


Figure 18: Groundwater contours with 5 m intervals[**]

[**] Geology background after CGS (2005)

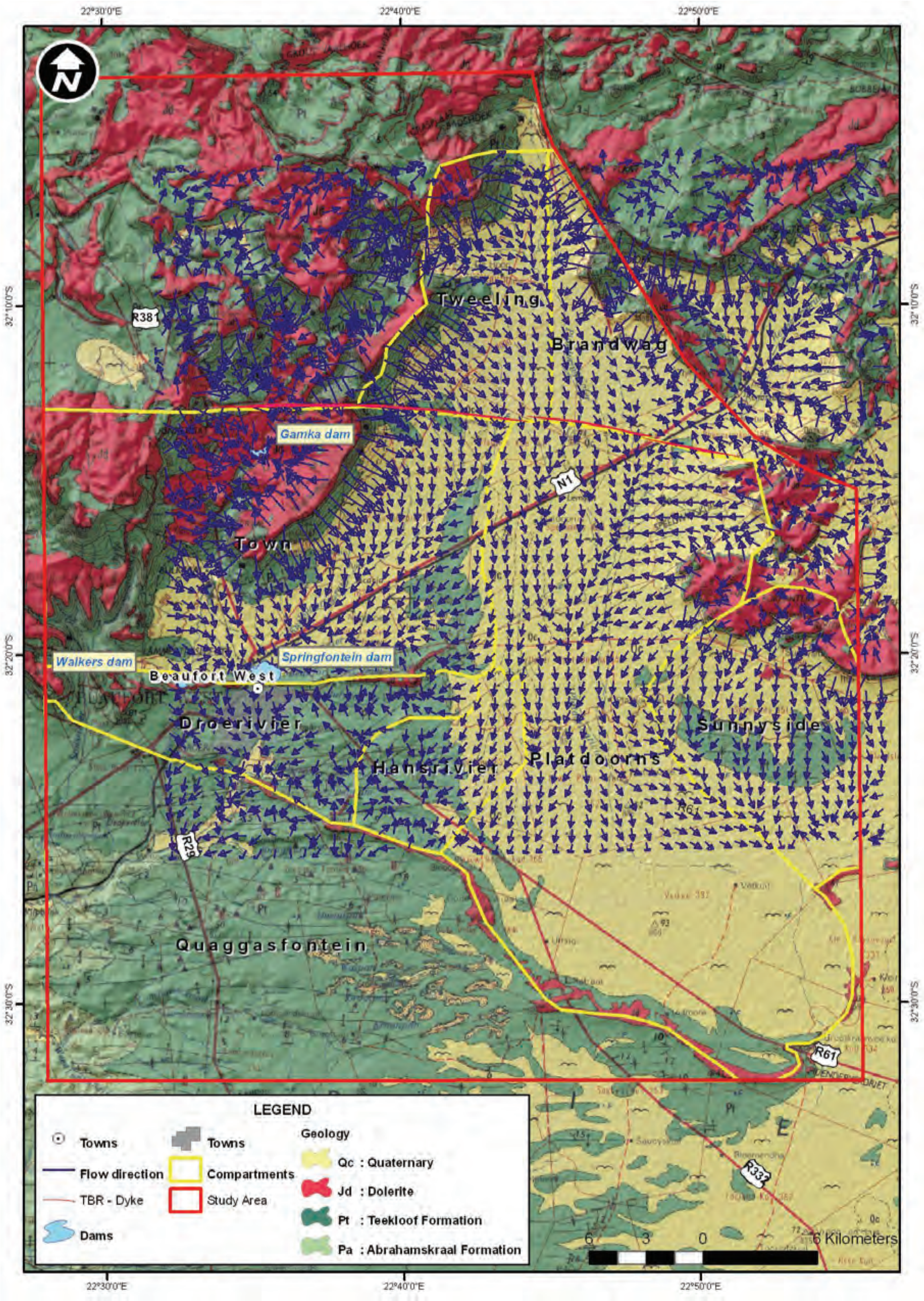


Figure 19: Groundwater flow direction and compartment[††]

[††] Geology background after CGS (2005)

The groundwater contours provided important information of the groundwater flow characteristics. Note that areas above 1010 mamsl were not contoured as there is very limited data above this elevation that would otherwise also make the map look too "crowded". It is also not sure how the aquifers with piezometric heads of over 1300 mamsl are linked to those below 1000 mamsl over such a relatively small distance. Hence it is likely that the boreholes in the Nuweveld Mountains could be linked to topographically higher aquifers. Distinct groundwater flow patterns were identified. Although the general groundwater flow direction is from north to south the dolerite dykes have a strong influence on the local groundwater flow conditions. This is best shown by the groundwater contours that straddle almost perpendicular to the strike of the dykes, implying that the groundwater flow is parallel to the strike of the dykes. Hence, the dykes (i.e. Town dyke, TBR dyke, Hansrivier dyke and Droerivier dyke) are essentially interpreted as groundwater barriers that effectively compartmentalise the groundwater flow.

The groundwater flow net enabled the identification of capture zones. The capture zones were manually identified using a simple approach: Where two arrows point away from each other a groundwater boundary (capture zone) is defined. Based on this approach several groundwater compartments were highlighted over the study area. These groundwater compartments are the Droerivier compartment, Hansrivier compartment, Platdoorns compartment, Sunnyside compartment, Brandwag compartment, Tweeling compartment and the Town compartment. Although no groundwater level data were sourced for the areas in the far south and southeast of the study area, and although these areas were initially not included into the Tripol grid, it was decided not to exclude them from the study since they overlap with large parts of the current active uranium mines. A simple extrapolation approach was then used to subdivide these areas into groundwater compartments based on 2 principles:

1) The general groundwater flow direction is from north to south.
2) Dolerite dykes are groundwater barriers.

Utilizing the extrapolation approach, the areas in the south and southeast were subdivided into the Quaggasfontein compartment, whilst the Platdoorns compartment was extended southwards up to the dyke (probably same dyke as Droerivier dyke) along the southeastern boundary of the study area.

The Droerivier compartment is situated south of the town. Based on the groundwater level contours the groundwater is draining from the north and northeast towards the southwest. The Gamka River is likely to be the main driving force behind this. Some leakage is expected across the Town dyke that will generally feed this compartment. The Town dyke marks the northernmost boundary of this compartment, whilst the Droerivier dyke is the southernmost boundary of this compartment. The groundwater quality is generally good (EC < 150 mS/m) particularly in close proximity to town, but tends to become poorer away from town towards the south and southwest.

The Hansrivier compartment is situated east of the Droerivier compartment. It is separated from the Droerivier compartment by the presence of the Hansrivier dyke, i.e. a small north-south dyke on the farm Hansrivier. Recent magnetic data showed that the Hansrivier dyke is not laterally extensive to the north and that it is cut off in the vicinity of borehole HR_14 on the farm Hansrivier. Hence north of HR_14 it is likely that some mixing occur with the fresher Droerivier compartment. The Hansrivier compartment drains from the north, east and southeast towards the west up to the Hansrivier dyke. Local recharge might also occur from the southeast within this compartment, but this can be confirmed with more groundwater level data in the south and southeast of this compartment. Based on field measurements the groundwater quality east and west of the Hansrivier dyke is distinctly different, i.e. > 150 mS/m east of the Hansrivier dyke and < 100 mS/m west of the Hansrivier dyke. Hence the Hansrivier dyke is generally regarded as a groundwater barrier.

The Platdoorns compartment is a large compartment that stretches from the TBR dyke in the north to the Droerivier dyke in the southeast of the study area. A local recharge area is identified in the northeast of this compartment coinciding with the mountains south of Renosterkop, from where groundwater is flowing initially in a westerly direction, then changing to a southerly direction as it approach the middle region within this compartment. Although the TBR dyke is mainly seen as an impermeable barrier, some leakage is expected across this dyke from the Brandwag compartment since the dyke is offsetting. This compartment generally has elevated ECs (> 300 mS/m) and poor borehole yields (< 2 ℓ/s) which further makes it a unique compartment.

The Quaggasfontein compartment spans the area in the southwest of the study area. The compartment is defined in the north and northeast by the Droerivier dyke, whilst in the south and west the boundary is defined by the study area boundary. The area is characterized by small open folds within the Teekloof Formation. In the southeast of the compartment there are several small dried up pans. Although there are very limited data in the south of this compartment, the general groundwater flow direction is assumed to be from north to south based on observations of the regional groundwater flow pattern. Hence it is also expected that the groundwater ECs will increase from north to south.

The Sunnyside compartment is the compartment in the extreme east of the study area. It is characterised by predominantly southerly groundwater flow from the mountainous area north of the farm Sunnyside to a dyke south of Sunnyside that appears to be a ring-like feature. The mountains at Sunnyside are also regarded as a local recharge area. Towards the southwest of this compartment some leakage is expected from the Platdoorns compartment. The groundwater quality in this compartment is much fresher than in the Platdoorns compartment with variable borehole yields > 5 ℓ/s reported here.

The Brandwag compartment is the furthest northeast compartment in the study area. The compartment is demarcated in the north, northeast and east by a prominent mountain range, whilst in the south the compartment is demarcated by the TBR dyke. The westernmost boundary is demarcated at a point where all groundwater is flowing exactly north-south, with no easterly component of flow (possibly a constant head boundary). Local recharge is from the northeast and north. Based on the interpretation of the groundwater level contours, no groundwater seems to be reaching the Brandwag compartment from the west along the TBR dyke. The latter statement contradicts previous assessments by SRK (1997). Although the EC is poor (along the eastern side of this compartment, this phenomena is very localised and probably aided by local dewatering of the aquifer. The current observation of declining water levels in this area suggests that this is possible. Therefore, although there is a groundwater component flowing from the east (i.e. from Renosterkop), this might have been caused by local over-pumping resulting in poorer quality groundwater being drawn in from the east. The borehole yields in this compartment are generally above 5 ℓ/s, and seldom below 2 ℓ/s.

The Tweeling compartment is situated west of the Brandwag compartment. Its southernmost boundary is the TBR dyke, whilst the western and northern boundaries are the Nuweveld Mountain. The eastern boundary coincides with an area identified as a constant head boundary. Groundwater flow is mainly eastwards along the TBR dyke and southwards from the Nuweveld Mountains (i.e. local recharge area). Some groundwater flow across the TBR dyke is expected towards the Platdoorns and Town compartments.

The Town compartment has the Town dyke as its southernmost boundary, although some groundwater flow across this dyke towards the Droerivier compartment is expected. In the north and west the Nuweveld Mountain provides the main recharge area. The extent of the capture zone could extend for kilometres into the Nuweveld Mountains, hence the northernmost boundary of this compartment is not well defined. For the purposes of this study the TBR dyke that outcrops in the pass north of town is used as the northernmost boundary. Groundwater generally flows from the north and northeast towards the southwest (town). Very good groundwater quality (< 150 mS/m) is generally encountered in the west along the Gamka river. Declining water levels are also known to recover quickly after rainfall events which further indicate good active recharge in this area. Groundwater quality in the eastern side of this compartment has slightly higher EC (70-300 mS/m), but could indicate greater travel distances from the recharge area.

6.2 Examples of applications

6.2.1 Borehole purging

To determine whether or not a monitoring hole needs to be purged, two boreholes were selected and tested on the farm Lombardskraal situated approximately 20 km Southwest of Beaufort West, to see the if purging had any effect on the field parameters measured. The result of pH-EC logs with depth in Olive2 borehole is presented in Figure 20.

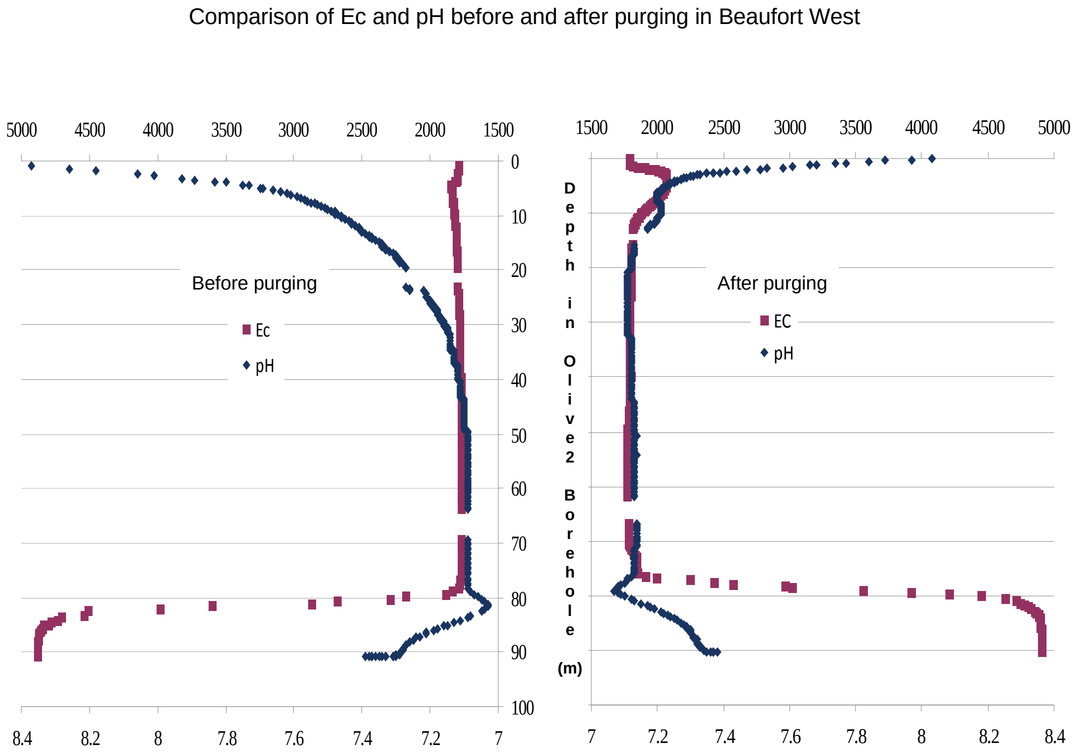


Figure 20: Comparison of EC (uS/cm) and pH profiles before and after purging.

Borehole Olive2 with coordinates S32.504900 and E22.565220 was tested on May 12, 2011 on the farm Lombardskraal situated approximately 20 km Southwest of Beaufort West, to see if purging had any effect on the field parameters measured on site. Before purging the borehole was logged with an YSI meter, which recorded temperature, pH and EC variations with depth in an undisturbed column of water (Figure 20).

The borehole, installed at the depth of 70 mbgl (static water level was 7.61 mbgl) was then purged at a rate of 0.8l/s for about 5 hours, whilst continuously measuring pH, temp and EC.

The logging information in the borehole typically display an active flow system on top, indicating low mineralised recently recharged water with more evolved highly mineralised/stagnant water occurring at the bottom of the borehole. EC and pH is uniform from about 20 to 80 m, whereby there is a sudden significant jump in the electrical conductivity at about 80 m depth. This might indicate a change in lithology or it could also be due to density fluctuations within the borehole column causing a pronounced stratification. The same borehole was logged in 2009 and shows almost an identical profile as to the one above. Interestingly though, it can be concluded that the purging would not have a significant influence on the overall profiles.

As discussed previously, the Olive2 borehole may be purged and equipped when monitoring for uranium radioactivity proceeds.

6.2.2 Compartmentalization

The primary purpose of groundwater utilization is for domestic water supply and limited supply for stock farming in BW. There are several wellfields that are identified including Brandwag East and West, De Hoop, Platdoorns, Lemoenfontein, Town well, Droeriver, Hansriver and Sunnyside (Rose, 2008). Among those wellfields, water resources evaluation in Brandwag and Lemoenfontein was evaluated in detail (SRK, 1998). Based on the local hydrogeological conditions and sources of contamination, a differentiated protection approach is examined and proposed in Table 7.

Studies on capture zones for simple flow conditions in uniform aquifers were performed by Todd (1980), Almendindger (1994) and others. For more complex flow situations where boundaries are considered, borehole capture zones or catchments may be delineated by using semi-analytical models (Nelson, 1978a,b; Keely and Tsang, 1983; Javandel and Tsang, 1986; Lerner, 1990 & 1992; Blandford and Huyakorn, 1991 and Kinzelbach et al., 1992).

Table 7: Adapted protection methods for various groundwater sources

Source type	Feature	Method	Implication
Spring	seasonal variation	Delineation of ZOC	cross compartments
Production hole	Operational variation	Compartment protection	Entire compartment
Standby hole	Operational variation	Compartment protection	Entire compartment
Potential aquifer	Decadal variation	Precautious protection against climate varibility	Conservative against redioactive contamination

The existing semi-analytical models provide a powerful tool to understand the capture zone concept and to acquire general ideas about borehole or wellhead protection zoning before embarking on a site-specific study of groundwater protection. However, these models do not account for the capture zone of a draining fracture. In South Africa, boreholes are often sited in highly fractured dykes for good water supplies. Strack (1989) and Haitjema (1995) presented the concept of the linesink which is utilized here to simulate a permeable dyke or fracture zone for delineating the capture zone in dyke aquifers.

A borehole protection area can be defined as the controlled area surrounding a production borehole (or wellfield). Demarcation of such controlled area where certain activities of land use are prohibited would prevent contaminants from reaching the borehole. It may consist of a capture zone as well as a borehole catchment. The latter, also referred to as the zone of contributing water (ZOC) (Todd, 1980; Reilly and Pollock, 1993), is the limiting case of the capture zone at t where $t = \infty$. The borehole catchment may be interpreted as the projection on ground surface of a 3D aquifer volume which would contribute water to the borehole under steady-state flow and pumping conditions. Inside the catchment water would flow towards the borehole whereas water outside would flow away from the borehole. The delineation of the protection area is often based on assumption of the averaged steady-state flow. Assuming A (L^2) is the area of the catchment, R (LT^{-1}) a uniform rainfall recharge and Q ($L3T^{-1}$) the averaged pumping rate from a borehole of interest, then the following relation holds: $AR=Q$. This relationship tells us that the borehole catchment size A can be calculated if R and Q are known. However, it gives neither a physical location of the catchment with respect to the borehole, nor does it provide hydrogeological conditions like type of aquifer etc. It merely provides water balance with many geometrical distributions possible as illustrated in Figure 21. Under steady-state conditions, groundwater streamlines coincide with fluid pathlines. If dispersion is negligible, we may use pathline equations to track pollutant movements in aquifers. To demarcate either a capture zone or a borehole catchment under the steady-state, we utilize discharge potential to derive the pathline equations. Assuming an aquifer thickness is more or less uniform, the pathline distributions under certain hydrogeologic settings are investigated in an x, y plane.

As dykes plays a most critical role in forming compartments in Beaufort West, potential contamination in production borehole should be assessed under the hydrological configuration. Against this background, an intervention policy must be proposed in terms of implementation of protection zones.

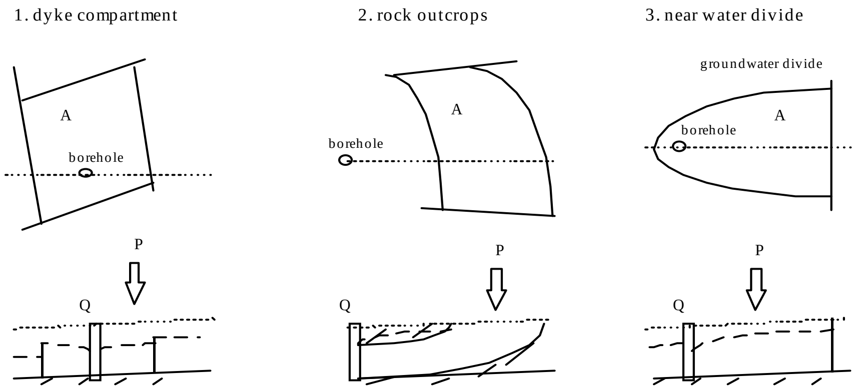
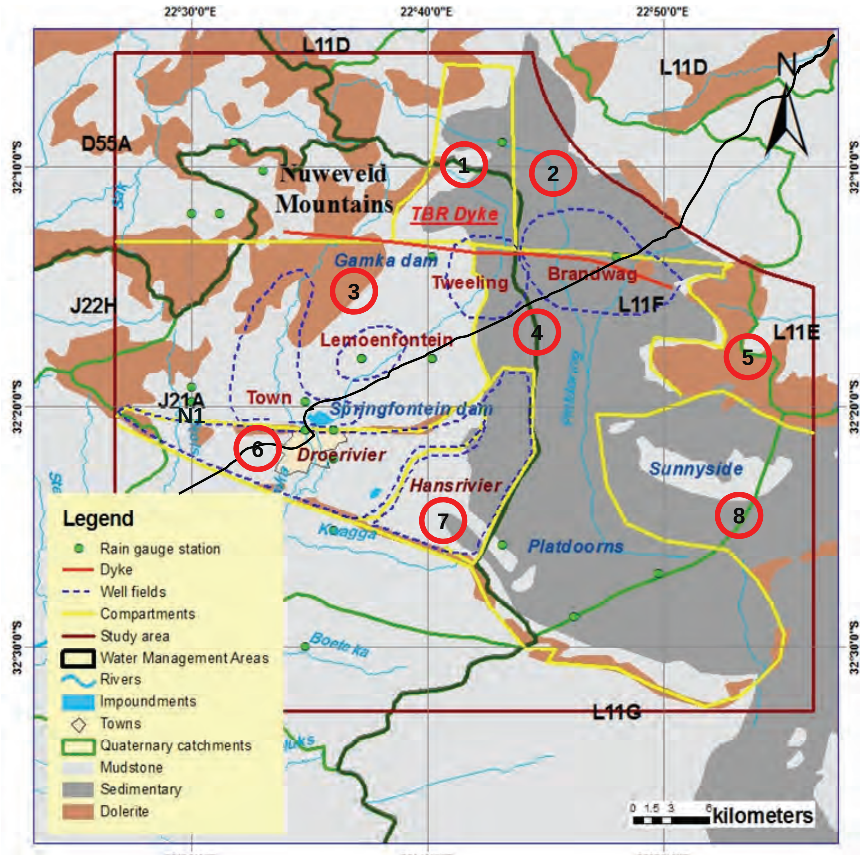


Figure 21: Possible locations of borehole catchment.

Jurassic age dolerite dykes and sills intruded into the fractures of the Karoo sediments over a period of extensive magmatic activity over the entire southern African subcontinent during the Gondwanaland break-up (Chevalier et al., 2001), resulting in a network of dolerite dykes, sills and even inclined sheets in the study area. The two main dykes are:

- E-W trending stretching from the Nuweveld Mountains north of the Gamka Dam in an easterly direction cutting across the farms Tweeling, Brandwag and Renosterkop, otherwise called the TBR-dyke by SRK (1997), terminating into an interpreted dolerite ring structure on the farm Renosterkop.
- E-W striking trending dyke cutting through the town of Beaufort West

In addition there are also other dykes like the Droerivier dyke (i.e. southeast-northwest dyke north of Droerivier) and Hansrivier dyke (i.e. a small north-south dyke at Hansrivier). Furthermore, there are dolerite sills that cover mainly the mountain tops as cap rock. The interpreted dolerite ring structure on the farm Renosterkop is described by Chevalier (2001) as saucer-like inclined dolerite sheet.



Code	Area (km²)
1	89.3
2	100.9
3	363.4
4	462.4
5	89.2
6	102.7
7	78.6
8	199.5

Figure 22: Identified wellfields and compartments for protection.

It is evident that the Beaufort West is characterised by compartmentalisation outlined by major and small dykes present in the area. This is further verified by groundwater flow features. A groundwater level contour grid was compiled over the study area to assist with the identification of groundwater flow paths. These flow paths contributed significantly in the delineation of groundwater compartments (Figure 21). The groundwater compartments are the Droerivier, Hansrivier, Platdoorns, Quaggasfontein, Sunnyside, Brandwag, Tweeling and the Town compartments. In fact, there are eight compartments that can be identified for the protection purpose (Figure 22). All the groundwater compartments seem to correlate well with spatial observations of EC and recharge. Based on 2 principles, i.e. 1) groundwater flow is from north to south, and 2) dolerite dykes are groundwater barriers, the Quaggasfontein and southern parts of the Platdoorns compartment were extrapolated southwards due to the unavailability of data.

A conceptual model through a N-S section through the Town compartment was compiled to illustrate the groundwater flow regime in a typical Karoo fractured rock compartment. Chemistry data (macro-chemical and isotope) were used to support the conceptual model. Based on the interpretation of the isotope data shallow and deeper groundwater flow systems were identified. The shallow groundwater system is linked to meteoric water, whilst the deeper groundwater system is linked to a relatively deep circulating water. It is believed that the Town dyke is therefore seen as a groundwater barrier (impermeable). The current municipal groundwater abstraction is from the shallow groundwater system.

Due to uniform flow dynamics within a compartment, those compartments with four municipal wellfields draining water from should be prioritised for protection purpose. Based on the configuration of a typical dyke compartment, a mass balance can be used to come out with possible management intervention (Figure 23).

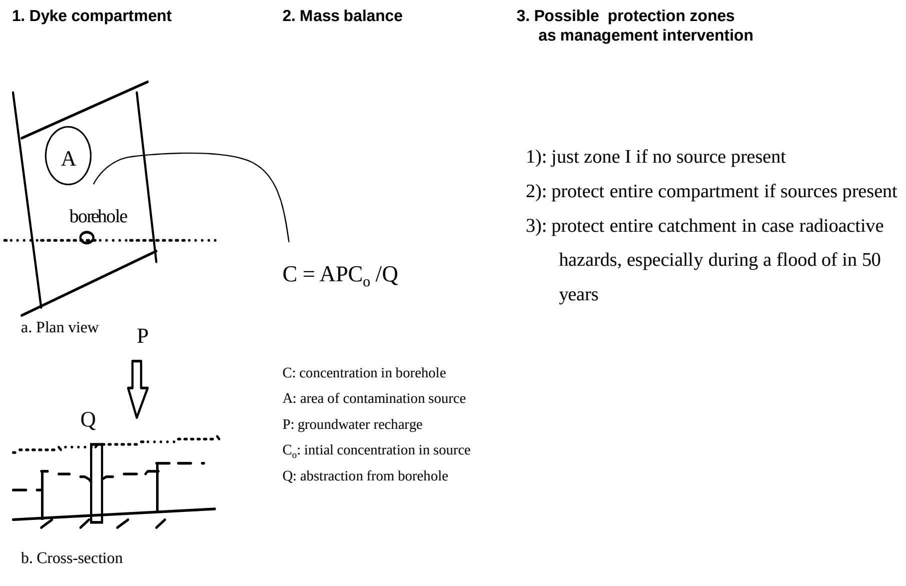


Figure 23: A configuration for dyke compartment.

6.2.3 Beaufort West Springs

Springs and shallow wells are probably still the common way of water supply to rural and even urban and peri-urban areas in South Africa. Major types of aquifers and their combinations in South Africa allow for a variety of spring occurrences. The most typical and generally observed springs include those located in a topographic depression, along a formation contact, major fault, joints, fracture zone and in the vicinity of Karst cavities as illustrated in Figure 24.

The Beaufort West Spring, situated on the contact of the Teekloof formation and the Town dyke, is linked to the deeper groundwater system. The Town dyke has a strong structurally controlled influence on both the shallow and deeper groundwater flow system since it forces the deeper groundwater upwards. Based on local hydrogeology and field verification, the Beaufort West Spring is classified as a contact spring, reflecting a seasonal outlet of an adjacent reservoir called Springfontein Dam within the Town wellfield compartment.

This spring is used for many purposes including recreation benefit for the Town itself. There its protection entails (1) not only maintenance of its environmental functional flow requirements (2) but also acceptable quality for the users.

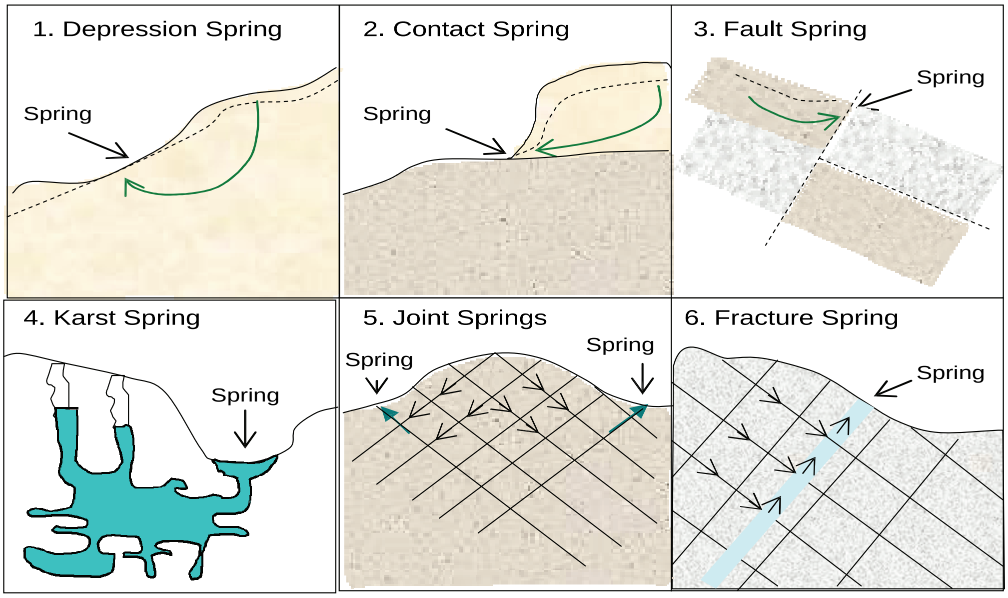


Figure 24: Types of springs often observed in field (modified from Harvey, 2004).

Spring protection is important aspect in modern hydrogeology. Various techniques including tracer experiment and vulnerability mapping have been applied to groundwater protection zone delineation in several fractured aquifer case studies but criteria for choosing one technique over another for protection zoning purpose are not readily available. In the case of the Beaufort West Spring, prevention of over-abstraction of groundwater in the upstream feeding compartment, i.e.

Town wellfield, and maintenance of spring flowing gradient are critical. However whether a priority should be given to the abstraction for water supply or meeting environmental requirements downstream needs to be resolved through a community participatory consultation process.

6.2.4 A worst case scenario

Uranium exploration in the Beaufort West area has been active for a number of years. Evidence of this is the number of exploratory boreholes that exist in the southeast and southwest of the town. These exploratory boreholes are different to the conventional water boreholes since the former are often very narrow in diameter (between 90 mm and 120 mm) and shallow, with maximum depths above the water level. Scholtz (2003) reported that some heavy metals including uranium element (U, Mo, Pb, Cu, As and Fe) with localised above-background values were evident in surface and groundwater, soils, sediment and crops. Though the heavy metal contamination was isolated by the lack of run-off and the dry climate experienced in the mining areas, the heavy metal content in surface water and sediment within the open pits on Rietkuil is especially high. These values pose a risk for human ingestion and may cause cancer in the long run. These pits are easily accessed without a fence, and are used for drinking sources for fauna and as a growth medium for flora. The easily accessed Cameron Shaft on Rystkuil Farm is also a concern due to the possible presence of the radioactive inert gas, radon.

The local farmers and land owners are unaware of the possible toxic effects of uranium and coherent heavy metals. This led to previous usage of superficial water, mine water for crop irrigation, moving and feeding of livestock as well as wildlife among uranium ore stockpiles, swimming in water-filled open pits and using crushed uranium ore for gravel road maintenance and construction.

A worst case scenario in respect of the proximity of the uranium trial mines situated in the vicinity of potential wellfields for Beaufort West Municipality can be described. Aquifers on the Farm Rystkuil are reserved for medium to long term exploitation with potential yields of 25 l/s (DWA, 2010). The high fluoride issue can be complicated by potential uranium contamination if no protection measures are in place. The area is topographically very flat. Should the mines be flooded, the municipal wellfields in the vicinity could be threatened by ingress of flooding water with high concentration of uranium into the aquifers used, or intended, for water supply.

The presence of uranium ore in stockpiles and the consequent effects on the water, soils, sediment, fauna and flora and possible human, prioritises the remediation and rehabilitation of uranium trial mining sites within the Beaufort West. A zone of inadequate remediated areas due to cessation of mining activities should be demarcated for the protection purpose. Education and awareness of potential uranium toxicity among the local community remain to be one of best precautious measures for the protection purpose.

6.3 Numerical modelling

The numerical modelling is used to simulate and verify various zoning scenarios. The particle tracking technique is especially useful to represent persistent pollutants (e.g. nitrate). The flow simulation is based on the assumption of groundwater steady flow conditions. As mentioned previously the town of Beaufort West is almost completely dependent on groundwater from the wellfields to the North and the town spring as a major water supply. Due to the local municipality and farmers competing for virtually the same resource the groundwater quality and water levels dropped and deteriorated significantly over the past 20 years. The town also has a spring, which seems to be supported by a shallow groundwater system and will be the focus along with the wellfields of particle tracking to delineate the zone of contribution (ZOC).

Based on existing wellfields, a composite aquifer incorporating basic features of the wellfields is conceptualised for the particle tracking purpose. The dyke aquifer has a thickness of 100 m with size of 13.63 Km^2, while an abstraction hole at a rate of 1145 m^3/d, which is a half of recharge, is placed 100 m away from the dyke which makes no-flow boundary on left side of the aquifer. The hydraulic conductivity used was 1.87 m/d. The simulation results, as seen in Figure 25, indicate (1) that the capture zones are progressive expanding with increasing travel times; (2) if 4-year cycle is a recharge cycle, the capture zone within one recharge cycle remains well within the averaged composite aquifer. This means that our protection strategy based on an individual compartment is adequate measure.

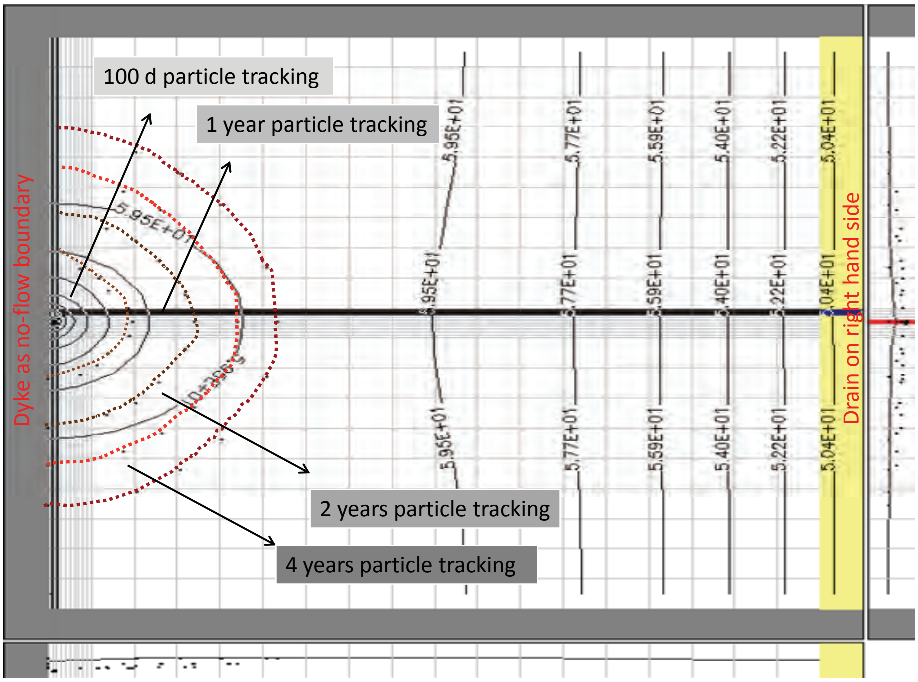


Figure 25: Capture zones delineated by particle tracking for a composite dyke aquifer.

Backward particle tracking can be useful in simulating flow paths under different pumping scenarios and see what effect the increased pumping has on the zone of contribution to the municipality well field and spring. Once this area has been demarcated by using the above numerical simulation technique, it will allow the local municipality to effectively manage and protect the well field status. Another important scenario is that the town is also undergoing uranium exploration, which might in the future pose a real threat to the groundwater resource. The area has an abandoned uranium mine South of Beaufort West in close vicinity to the Hansrivier wellfield, which is also earmarked as a future water supply option. Should this mine flood during periods of above average rainfall, it could reverse the whole groundwater flow regime and contaminate the groundwater with radioactivity. It thus becomes even more important to demarcate a zone of contribution, which accounts for this perceived danger.

6.3.1 Flow simulations

The numerical modelling is used to simulate and verify various zoning scenarios. The particle tracking technique is especially useful to represent persistent pollutants (e.g. nitrate). The flow simulation is based on the assumption of groundwater steady flow conditions. As mentioned previously the town of Beaufort West is almost completely dependent on groundwater from the wellfields to the North and the town spring as a major water supply. Due to the local municipality and farmers competing for virtually the same resource the groundwater quality and water levels dropped and deteriorated significantly over the past 20 years. The town also has a spring, which seems to be supported by a shallow groundwater system and will be the focus along with the wellfields of particle tracking to delineate the zone of contribution (ZOC). Backward particle tracking can be useful in simulating flow paths under different pumping scenarios and see what effect the increased pumping has on the zone of contribution to the municipality well field and spring. Once this area has been demarcated by using the above numerical simulation technique, it will allow the local municipality to effectively manage and protect the well field status. Another important scenario is that the town is also undergoing uranium exploration, which might in the future pose a real threat to the groundwater resource. The area has an abandoned uranium mine South of Beaufort West in close vicinity to the Hansrivier wellfield, which is also earmarked as a future water supply option. Should this mine flood during periods of above average rainfall, it could reverse the whole groundwater flow regime and contaminate the groundwater with radioactivity. It thus becomes even more important to demarcate a zone of contribution, which accounts for this perceived danger.

6.3.2 Criteria for use of 2D and 3D modelling

It is inevitable to ask a question like: under what circumstance either 2D or 3D modelling should be used? It is often questioned whether the extra effort of a 3D numerical simulation is justified. The answer does not seem a straightforward one.

In general, groundwater flows slowly and laminar flow, sometimes known as streamline flow, may occur when a fluid flows in parallel layers, with no disruption between the layers. In this case, a 2D simulation for flow and particle tracking could suffice. In laminar flow the motion of the particles of fluid is very orderly with all particles moving in straight lines parallel to the aquifer boundary. Hence particle tracking can be used to represent movement and distribution of no reactive contaminants in groundwater protection zoning.

When a fluid is flowing through an abstraction point such as a partially penetration borehole or interaction zone with surface water bodies, the 2D simulation may not be sufficient to capture flow characteristics. In this case a 3D modelling may deem necessary.

Depending on hydrogeological settings, stress exerted on the aquifer and flow dynamics, either 2D or 3D can be used to simulate groundwater flow for the purpose of delineating a protection zone or ZOC (zone of contribution) as illustrated in Figures 26 and 27. As many factors play roles in selecting either 2D or 3D model, two groups of parameters can be identified to formulate criteria.

- The first group includes Q (abstraction), R (recharge flux) and S (size of model domain);
- The second group deals with the extent of borehole penetration in the aquifer, which can be expressed by L (a borehole depth) divided by H (thickness of the aquifer).

For instance, a laminar flow would be preserved if abstraction Q is smaller than the recharge input, R, over area S, i.e. $Q/RS < 1$. For a complete penetration borehole, i.e. $L/H = 1$, groundwater flow can be simulated by using a 2D model as long as Q is relatively smaller than RS.

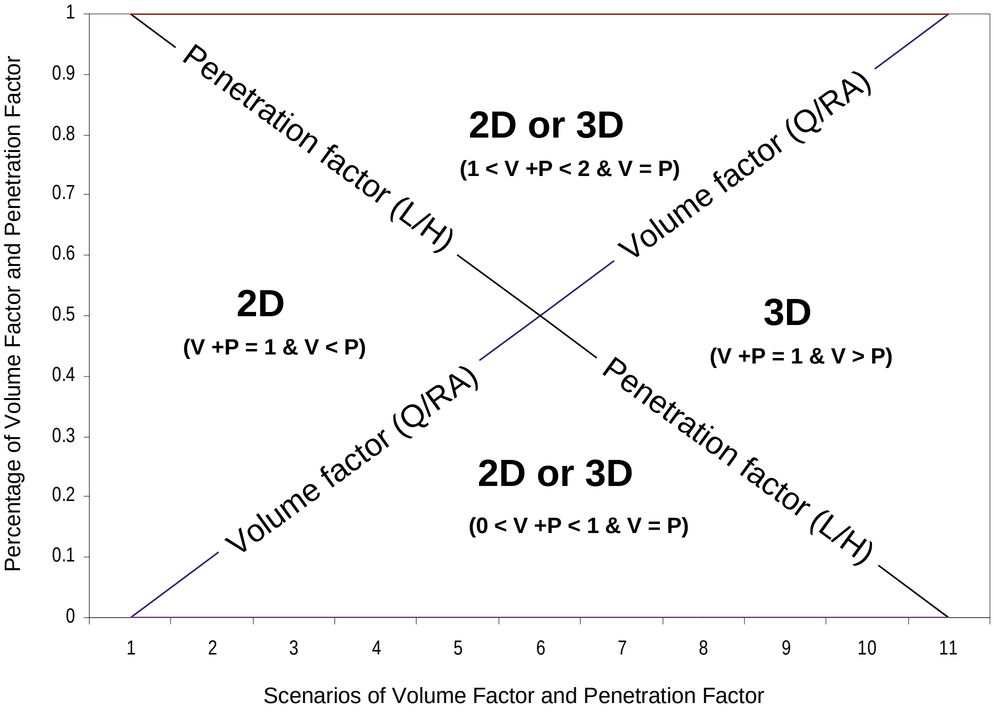


Figure 26: Criteria of 2D and 3D models.

A factor V may be formulated to consist of: $V = Q/(SR)$ where S (L^2) is the size of investigated area or recharge area, R is rainfall recharge. If V is considered together with ratio $P = L/H$, where L is the slotted casing length and H is the aquifer thickness as similarly defined above. The difference between 2D and 3D solutions would diminish under the following condition: $V + P = Q/(SR) + L/H = 1$ and $V >$ or $< P$. If the vertical axis represents a percentage of volume and penetration factors, and horizontal axis demarcates scenarios of V and P factors combinations, zones of 2D, 3D and both combination can be differentiated. As shown in Figure 26, four areas are demarcated by two lines crossing at central point labled with Penetration factor and Volume factor, respectively. Furthermore, in Figure 27 where the vertical axis represents a dimensionless volume (V) and horizontal axis demarcates a dimensionless penetration factor, the zone of 2D and 3D simulations may further be demarcated.

Based on Figures 26 and 27, four classes can be differentiated as follows:

- $V+P \leq 1$ and $V<P$ for 2D;
- $1 < V+P \leq 2$ and $V>P$ for 3D;
- $0 < V+P < 1$ and $V>P$ for 2 or 3 D;
- $1<V+P<2$ and $V<P$ for 2 or 3D.

The above criteria can be used as rough guide to whether a 2D or 3D model must be used for flow and particle tracking simulation for the purpose of demarcating the protection zones.

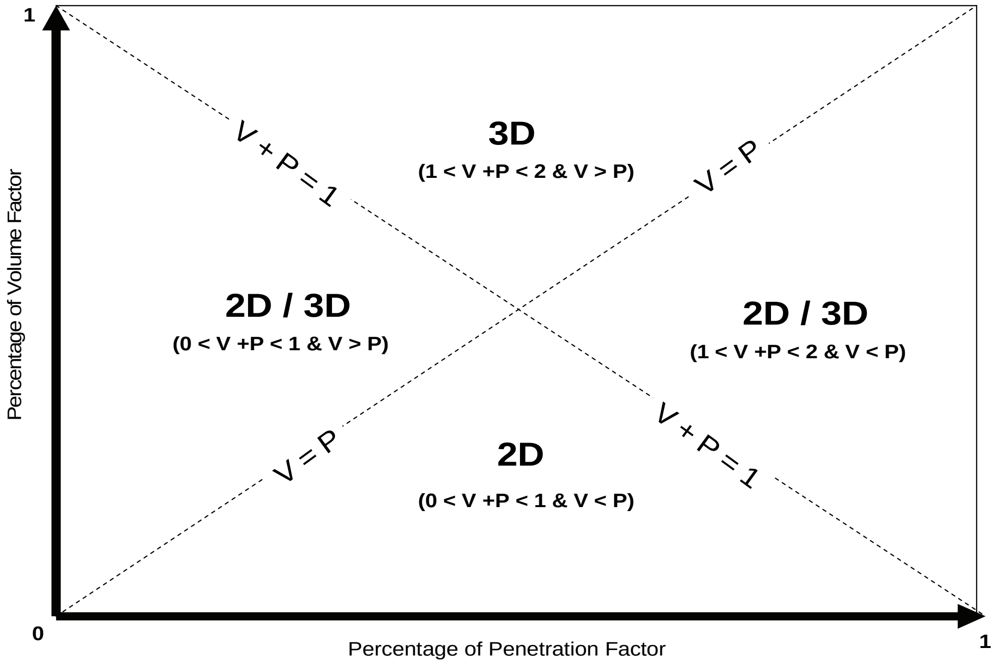


Figure 27: Criteria of 2D and 3D models (b).

7. UNDERTAKING A SAMPLING PROGRAMME

The review of flow patterns, hydrochemistry and radiochemistry in the various aquifers that are (potential) water sources for the town, indicates that there is a need for monitoring these aquifers to safeguard ensure their future safety. For this purpose proper sampling and monitoring procedures should be in place (Mahed, 2010). A protocol for this process is the subject of the following two chapters.

One should distinguish between the initial sampling programme (named 'pilot sample run' by Weaver et al. (2007)) and the actual monitoring programme. During the sample run, a wide range of parameters should be analysed from a large number of sources (typically boreholes). The results of the sample run, together with all other available information enable one to develop a monitoring programme that can be repeated as many times as necessary.

The monitoring programme follows on an evaluation of the data from the sampling programme. The object of monitoring is to detect changes early enough to be able to take some remediate action. Examples are guarding against likely pollution events (as in Beaufort West and in the vicinity of landfill sites), forecast of earthquakes by semi-continuous radon monitoring in groundwater and early detection of leakages in industrial settings. Many of the concepts of sampling for hydrochemistry Weaver et al. (2007) are also valid when sampling for radio-nuclides. Radionuclides are special in the sense that their analysis is more costly, that the levels are generally very low, but can potentially also be quite high, the lack of general knowledge of the behaviour of radio-nuclides in nature and the public perception of the potential danger of some radionuclides.

Factors that are relevant are the nature of the sampling method, the parameters to be analysed, the choice of analytical method and the frequency of sampling. These are all dependent on the questions asked, the magnitude of the natural fluctuations of the radio-nuclide, the cost involved and the price of not being in time with the warning.

The procedures outlined in the following chapter are protocols for a sampling and monitoring programme. While the aim and motivation for this work is located around the Beaufort West situation, the protocols, with some local adaptation, are just as valid elsewhere

7.1 Pre-sampling procedures

Preparation for monitoring uranium isotopes in aquifers concerned is prerequisite for the correct sampling. Before going to the field the personnel involved in the sampling and monitoring should be well prepared (Weaver et al., 2007). The essence is that the project leader should establish what needs to be done, what samples to take, how records are to be kept, what data will be required, how the data will be processed and what the expected outcomes will be. The field staffs need to be sufficiently informed as to the plan, what their role is and how they are permitted to deviate from the plan in the case that the circumstances in the field happen to change. It is essential that good records are kept of sampling details; preferably in more than one form: hardcopy and soft copy. At all times it is important to involve the local stakeholders (municipalities, mines, land owners, water user association). These stakeholders are the ultimate recipients of the service and can provide local assistance and local knowledge.

When considering sampling preparation and design, it is important to distinguish between degradable and non-degradable contamination. In the case of degradable contamination (i.e. pathogens and bacteria) the concentration of these contaminants are influenced by seasonal flood events. However, due to Beaufort West being semi-arid and not receiving significant amounts of precipitation the potential for flooding events are very small and thus sampling (2 x per month) is recommended. Non-degradable contamination such as radionuclides of uranium requires a different approach that also needs to take into account the local climatic conditions and flow regime. Ideally, a uniform distribution of sampling sites is needed, however due to the fractured rock aquifer system being compartmentalized taking one sample per compartment would suffice as the radioactivity in Beaufort West being very close to background conditions. Seasonal variations can have an effect on radionuclide contamination it is therefore suggested that the borehole of interest be sampled once before and after a flood event and see how concentrations compare.

The utilization and development of uranium sources can vary from place to place as a result the procedure for sampling and monitoring would change accordingly. The two cases should be differentiated. If the mine is operating or closed a permit may be sort prior to conducting sampling and monitoring. If at the stage of exploration then the procedure would be simplified as no permit would be required. However, the consultation with the exploration agent has to be made to facilitate smooth operation on site. This would be an important step which led to objective assessment of the status of the uranium utilization.

Before any sampling and monitoring programme can be implemented it is necessary to achieve the best possible understanding of the geological and hydrogeological conditions in the area of interest. Knowledge of the flow conditions, (i.e. recharge, storage and discharge) and potential contamination migration routes is essential to plan the sampling strategy.

In addition the local infrastructure (roads and climatic condition should be assessed with the objective to develop localized sampling and monitoring protocol modus operandi.

This section deals mainly with the procedures to be followed prior to sampling for radioactivity and complies with international best practice. It consists of a stepwise approach in order for the intended user to become familiar with the various steps involved.

Weaver et al. (2007) outlines a comprehensive planning program which delves into pre sampling procedures. This includes a list of field equipment and general groundwater sampling procedures. These practical tips are of the utmost importance when preparing to venture into the field.

As part of the pre-sampling procedure acquiring permission from land owners as land tenure can be a complex issue in South Africa due to the historical reasons. In many instances boreholes are located either on private property or tribal land. In the case of private property, it is crucial that farmers or landowners are consulted prior to sampling. In the case of tribal land, the village headman or chiefdom is consulted beforehand. This consultation process is always helpful due not only to the fact that the land ownership can be respected but also because they might be able to provide valuable information with regards to environmental factors in the area as well as local history, as shown by Rose and Conrad (2007) in Beaufort West.

Lastly it is necessary to liaise with the laboratory in order to ascertain which containers, preservatives and reagents are to be used when sampling for radionuclides (Weaver et al., 2007). It is important not to only use gross alpha and beta measurements for estimating dose contributions from the radionuclides that are not individually measured. This is due to the uncertainties inherent in the determination of gross alpha and beta activity, which is typically around 20% to 30%. It therefore becomes necessary to analyze for the full spectrum of radionuclides of the uranium decay chains to get the concentration of individual isotopes.

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The different acids and methods used are due to the varying procedures of the laboratories. Therefore one would have to liaise with the laboratory of choice in order to determine the specific volumes of water required for analysis, types of bottles, treatment and storage of samples, among other things.

7.1.1 Sampling hole location

The sampling location must be able to reflect intended geological formation. As there is the extensive alluvial cover, in forms of pebbles and gravel sediments or calcrete, on top of the Beaufort Group, the sampling hole should be in the bedrock comprising mudstones, siltstones and sandstones. In addition, flow regime should also be considered as a sample must represent uranium concentration of specific formation water flows through.

As sampling devices may affect sampling collecting efficiency and accuracy, it is essential that an acceptable device be adopted for sampling purpose. Wilde et al. (1998) recommended that the acquired sample be representative of the in situ conditions. Thus the devices used to sample the groundwater are of the utmost importance. Barcelona et al. (1985) substantiated this point by mentioning the important characteristics of a sampling device:

- The device should be simple to operate to minimize the possibility of operator's error.
- The device should be rugged, portable, cleanable and repairable in the field.

- The device should have good flow controllability to permit low flow rates (= 100 mL/min) for sampling volatile chemical constituents, as well as high flow rates (> 1L/min) for large-volume samples and for purging stored water from monitoring wells
- The mechanism should minimize the physical and chemical disturbance of groundwater solution composition in order to avoid bias or imprecision in analytical results.

Barcelona et al. (1985) have further shown that the low flow sampling devices, which are used for Radon sampling, do not greatly, affect the radon concentration. Thus these devices, like the bladder and submersible pump, are all aptly suited for sampling and fit the criteria previously mentioned by Barcelona et al. (1985). It is noticed that the above mentioned devices are not only expensive but also designed for the Radon rather than the uranium species of interest. Attention should also be paid to more cost effective methods of sampling such as using the bailer or submersible pump. However either of two may not be an advisable option in boreholes intersecting multiple fractures due to the fact that it would sample water from the entire column and not at a specific depth or fracture. Again, what sampler is to be used should be assessed case by case with the same principle as introduced above.

7.1.2 Design of monitoring boreholes

Monitoring design of boreholes should have certain requirements or specifications in order to detect the radioactivity concentration in certain positions of the flow path, therefore not all boreholes meet this requirement. As a result design of the monitoring network becomes necessary, especially for the development of new monitoring boreholes.

The controlling factors in borehole installations are usually sanitation, stability, and an estimated minimum useable well life of 25 years (Kovalevsky et al., 2004). EPA (1992) concurs with the aforementioned and categorically state that the monitoring well casings and screenings should:

- be resistant to chemical and microbiological corrosion and degradation in contaminated and uncontaminated waters
- be able to withstand the physical forces acting upon them during and following their installation, and during their use
- not chemically alter ground-water samples, especially with respect to the analytes of concern

Kovalevsky et al. (2004) are of the opinion that the entire length of the well should be uncased. Despite this the aforementioned authors immediately contradict themselves and categorically state that in order to prevent collapse, especially in unconsolidated rocks, wells should be cased. Barcelona et al. (1985) state that is when wells are slotted along their entire length, water samples from these wells are indicative of water quality stemming from the entire well and not specific fractures. Therefore it is advisable to screen wells only at the depths of the fractures (Cook, 2003).

It could also be said that when constructing a monitoring well, in consolidated formations, it would be advisable to install screens at the depths at which fractures occur. Another option would be cordoning off of the individual fractures with the same well. This could be done by means of permanent packers or individual seals. However the effectiveness of the well seals between intervening monitoring points is often suspect and the care and time necessary to properly seal these types of wells are not justified when compared to the straightforward procedures for sealing separate holes for vertically nested wells (Barcelona et al., 1985).

The EPA (1992) suggests the use of PTFE (polytetrafluoroethylene) when constructing a monitoring well screen due to its resistance to radiation, oxidation, chemical and biological attack as well as weathering. Some advantages and disadvantages are shown in Table 8. (EPA, 1992),

Due to these disadvantages PVC has also been recommended as a suitable material for the construction of screenings and well cases. This is due to the fact that it is much cheaper and far more resistant to Acid Mine Drainage. (Weight and Sonderegger, 2000). According to the EPA (1992) other advantages of PVC include:

Table 8: Comparison of using PVC in borehole design.

Advantages	Disadvantages
Can be used under a wide range of temperatures;	Only slotted casing is available for screens;
Inert to attack by the environment, acids, and solvents;	Non-stick nature of PTFE may cause annular seal failure;
Fairly easily machined, molded, or extruded;	Moderate weight and low strength per unit length;
Most inert casing for monitoring metals	Ductile behavior of PTFE ("creep" or "cold flow") may result in the partial
Can be used under a wide range of temperatures;	Closing of well intake openings (i.e., screen slots);
Inert to attack by the environment, acids, and solvents;	PTFE casing and screen is unsuitable for driven wells; and
Fairly easily machined, molded, or extruded;	Higher cost relative to PVC (Polyvinyl chloride).
Most inert casing for monitoring metals	Only slotted casing is available for screens;
Can be used under a wide range of temperatures;	Non-stick nature of PTFE may cause annular seal failure;
Readily available	
Low maintenance	
Lightweight for ease of installation	
Flexible and workable	
Low cost relative to PTFE	

Unfortunately PVC also has its disadvantages. These are minimal when compared with other materials and thus the reason for it being so widely used in the construction of wells (Weight and Sonderegger, 2000). (EPA, 1992) states the following as disadvantages for the use of PVC in well construction:

- Unsuitable for driven wells
- May fail if subject to high temperatures
- May fail if subject to high pressures
- Long-term exposures of some formulations of PVC to the ultraviolet rays of direct sunlight (above-ground portions of casings) and/or to low temperatures may cause brittleness and gradual loss of impact strength that may be significant.

These materials have been highlighted due to their suitability for sampling radioactive elements (EPA, 1992). Therefore the use of any other material, specifically in well and screen construction, would not be advocated. This is in order to maintain the integrity of the groundwater sample as well as the results stemming from the analysis.

In the case of existing open boreholes, adaptation must be made to achieve the same monitoring objective. The reason for this is that the borehole is vulnerable to surface contamination due to oxidation influencing the radioactivity concentration. The borehole will then need to be capped and purged as mentioned under section 4.1.3.

Based on the above discussion it is recommended that in the first instance the design of boreholes for monitoring must be design in such a way that the monitoring becomes efficient in capturing data on radioactivity concentration in groundwater. For the case of monitoring existing boreholes the borehole must be duly adopted to maximize efficiency in data acquisition for the radioactivity. A discussion with staff of DWA Bellville Office suggested that the existing boreholes with auto loggers installed could also be used for understanding of flow regime, those boreholes including G29937B, G29879BS and G29898Ta (Piet Havenga, Pers. Comm., 2011).

7.1.3 Drilling methods

In South Africa, there are three levels (national, regional and local aquifers) of monitoring networks for groundwater quantity and quality, which are administered by the Department of Water Affairs. For instance, these monitoring boreholes in Beaufort West region are directly managed by the Western Cape Branch of the Water Affairs. Some of the existing holes may be used for the radioactivity monitoring purpose. But the need of new monitoring holes may not be ruled out completely. A decision of borehole selection will be taken through consultation with the Western Cape branch of the Water Affairs and local municipality.

Drilling method should be considered when a new borehole is constructed for sampling or monitoring purpose. There are a variety of drilling methods but for fractured rock aquifers the following list should be considered.

It must be pointed out that for a new borehole to be drilled primarily for taking samples, the borehole diameter should be smaller than that of the water supply boreholes. In addition to that the following lists are important factors to be considered during drilling procedures (EPA, 1992):

- Drilling should be performed in a manner that preserves the natural properties of the subsurface materials
- Contamination and/or cross-contamination of ground water and aquifer materials during drilling should be avoided
- The drilling method should allow for the collection of representative samples of rock, unconsolidated materials, and soil
- The drilling method should allow the owner/operator to determine when the appropriate location for the screened interval has been encountered
- The drilling method should allow for proper placement of the filter pack and annular sealants.
- The borehole should be at least 4 inches larger in diameter than the nominal diameter of the well (borehole) casing and screen to allow adequate space for placement of the filter pack and annular sealants
- The drilling method should allow for the collection of representative groundwater samples.
- Drilling fluids (including air) should be used only when minimal impact to the surrounding formation and ground water can be ensured.

As the protocol is primarily for the fractured rock environment, in the following sections we introduce the rotary, air rotary and other drilling methods for sampling or monitoring in order of importance.

7.1.4 Downhole logging

Prior to purging it is suggested that downhole logging be done. This would help to identify fractures within the subsurface (Cook, 2003). As demonstrated by Nel (2011), anomalous increases in certain parameters (EC and Temp) infer the location of a fracture within the borehole (Figure 28). This would only occur if the well or borehole is screened at various intervals, or is entirely uncased. Furthermore, various in-situ parameters such as temperature, pH, electrical conductivity, dissolved oxygen as well as some dissolved ion concentration could be determined in the borehole, depending on the type of logging tool used (Weaver et al., 2007). Caution should be taken when interpreting the logging data as these anomalies could also infer a lithology change or even stagnant water at the bottom of a well, thus care should be taken when interpreting the logs.

Gamma ray logs, which are a form of radiation logging, would have to be the most applicable to radioactivity studies due to their ability to detect radioactive material within fractures (NRC, 1996). It has been previously shown that radioactive daughter isotopes concentrate in and around the immediate vicinity of the fracture due to leaching from the parent rock (Wood et al., 2004; NRC, 1996).

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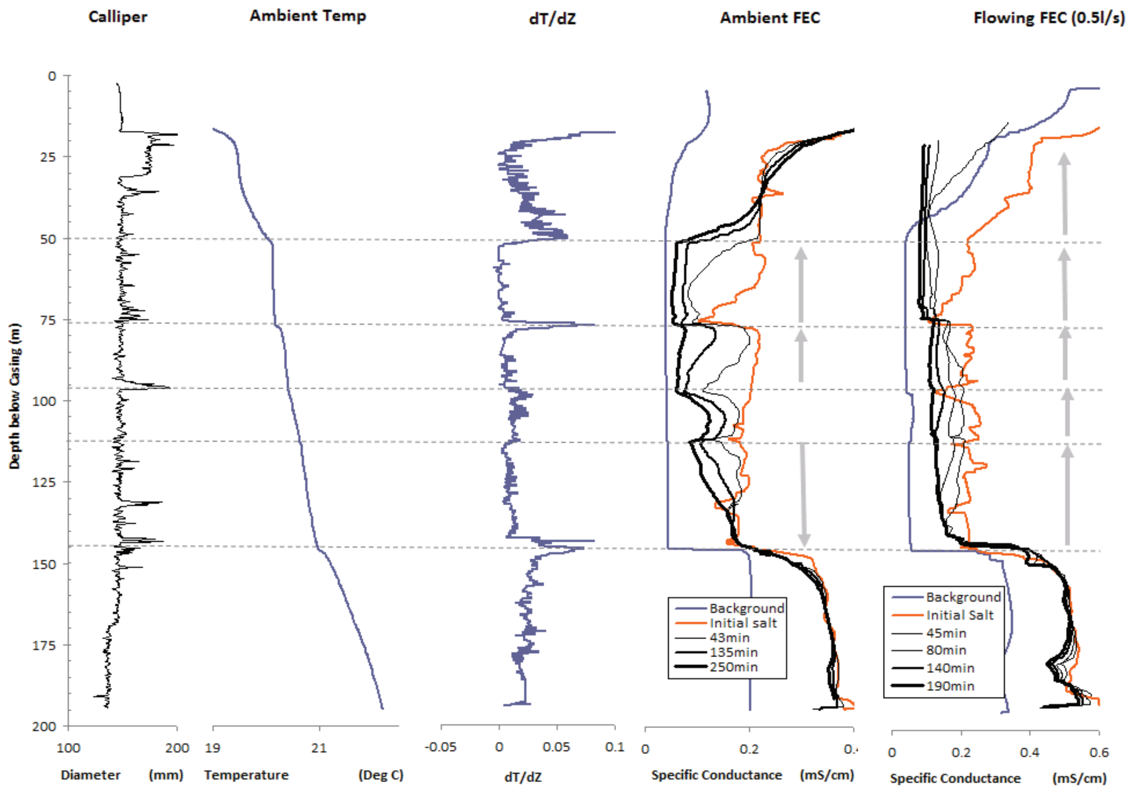


Figure 28: The use of temperature and electrical conductivity logging to determine fracture location at BH3 of the Gevonden fractured rock research site in the TMG (Nel, 2011).

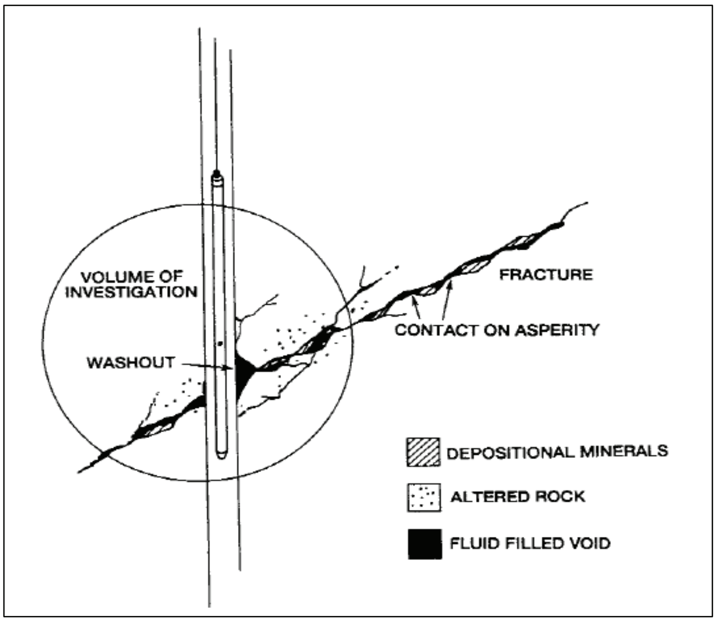


Figure 29: Schematic diagram of a natural fracture intersecting a borehole (NRC, 1996)

Recently FEC (Fluid Electrical Conductivity) measurements were taken to verify and identify fracture positions and associated flow flux in Gevonden BH3, Table Mountain Group (Nel, 2011). Nel (2011) indicates that flow rates, positions and quality of the fractures intersecting the BH3 can be established.

It is advantageous to use EC as an indicator for uranium sampling. As discussed by Brunke (1977), the abundance of U in subterranean waters is strongly related to the major components, of which the EC provides a rough approximation. The mean U/EC x 10-2 ratio for 35 Rietkuil waters was calculated at 1.3, which should provide a basis to discriminate between U values related merely to the water quality and those due to mineralisation.

Despite all of this there are some inherent problems when logging wells or boreholes in fractured systems. The initial alteration of the rock material in the immediate vicinity of the borehole could be attributed to drilling (Figure 29). This is further discussed in the following section. Also the area which could possibly be scrutinized is in the immediate vicinity of the hole and is quite limited. The combination of these factors could lead to misinterpretation of the underlying geology (NRC, 1996). Thus it has been shown that the combined use of a various methods yields better results and minimizes the misinterpretation of data (Cook, 2003). Furthermore certain field parameters which could be used in downhole logging are discussed in more detail in the following section.

7.1.5 Purging

Before taking a sample the well (borehole) should be purged. This is done in order to remove the stagnant water that may not be representative of groundwater in aquifer. Cook (2003) has compared sampling results prior to purging as well as post purging. The author has concluded that the radon concentration within the well varies greatly due to the ability of the gas to diffuse (Figure 30). Thus a sample taken from an unpurged well would not be representative of in-situ conditions of the aquifer. This is especially true in fractured rock aquifers due to the effect of preferential pathways.

Also the well should be purged using a low flow approach (Puls and Barcelona, 1996). This minimizes the oxidation of the sample and thus the alteration of in-situ chemical conditions. After the borehole has been purged the fractures would then be de-watered, followed by the matrix (Cook, 2003). This has important implications for chemical analysis as the conditions within a fracture differ to those of the matrix. It is especially important with regards to radionuclides due to the fact that we find an increase in Radon within these fractures (Wood et al., 2004). Cook (2003) has shown that the volume of water which should be purged must equate to two well volumes. It is critical to note that low flow sampling does not equate to purging (Weaver et al., 2007)

After purging the well the use of a flow through cell would be advised. This is done in order not to expose the sample to the atmosphere and thus alter its chemical or physical state (Weaver et al., 2007). The flow through cell seems to be the best tool for direct field measurements, due to the ability of the device to measure multiple parameters (Wilde et al., 1998). When taking the sample the utmost care should be taken in order not to contaminate the sample.

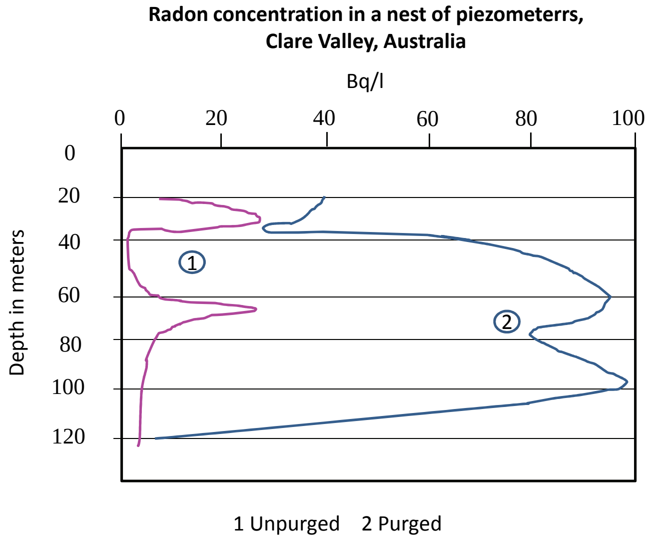
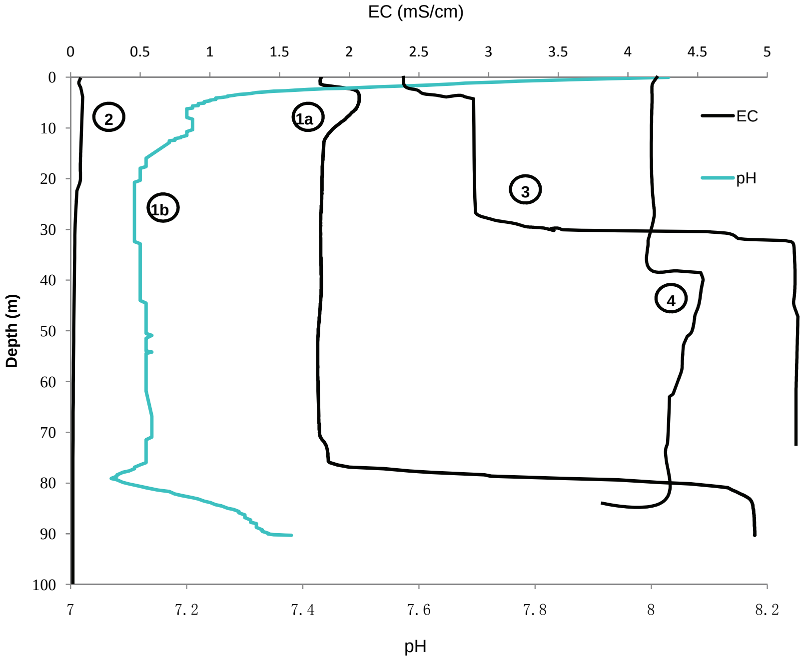


Figure 30: A comparison between the Radon concentrations before purging (pink) as well as after purging two well volumes (blue) (Cook, 2003)

Most aquifers are the fractured rock in South Africa but EC and pH can have a wide range of variation dependent on types of aquifers and their flow regimes conditioned by recharge and discharge. For instance, Figure 31 shows typical EC and pH profiles in some aquifers in the country. Three classes may be postulated as 1) high yielding production boreholes; 2) extremely low yielding boreholes with wellbore storage and 3) boreholes in between cases 1) and 2). For high yielding boreholes, there is no need to purge the borehole for uranium sampling. The purging is highly recommended for the extremely low yielding boreholes. For boreholes between above two cases, it must be judged case by case as the configuration of particular fractures in a borehole may dictate flow regimes of interest.

A lot has been mentioned in the protocol regarding onsite sampling after purging the borehole and allowing the field determinants to stabilize before taking samples for radionuclide analysis. It is recommended that packers be used to isolate the fracture zone and take representative samples at specific depths in the borehole. This should be used in conjunction with low flow sampling and flow through cells so that in addition to getting samples that are representative of the aquifer medium the parameters can also be reported with a high level of confidence. Samples are then taken following the procedure outlined in the protocol as summarized in Figure 35 and sent to the relevant laboratories for analysis.



Typical EC profiles in some aquifers in South Africa: 1. Olive2, Beaufort West (pH in 1b); 2. Rawsonville, TMG; 3. Kruger National Park Basalt; 4. Sandveld, Piekenierskloof Formation, TMG.

Figure 31: typical EC and pH profiles in some aquifers in the country.

7.2 Sampling devices

7.2.1 Bailers and pumps

For sampling equipment, submersible pumps are suitable. Bailers, grab samplers and syringe devices are not suitable because they cause disturbance and dislodge material from the borehole sidewall. For more information, the reader is referred to Weaver et al. (2007).

7.2.2 Packers

The isolation of specific fractures in order to understand their hydrogeochemistry is critical. This can be done by using packers. These inflatable devices are placed above and below the fracture of interest, in order to isolate the area (Figure 32). Prior to this a pump is isolated within the structure. USGS (2001) has designed the BAT3 (Bedrock Aquifer Transportable Testing Tool) specifically for sampling in fractured rock aquifers (http://toxics.usgs.gov/pubs/FS-075-01/, last accessed on 29June 2011). Besides having packers and a pump it is also installed with three pressure transducers. One is located above the packers, between the packers and the last one is below the packers. These are utilized in order to monitor fluid pressure and correctly ensure that the packers are properly isolating the fracture of interest (USGS, 2001)

Puls and Barcelona (1996) strongly recommend that low flow sampling, in conjunction with packers, should be done in fractured rock aquifers. This approach should only be attempted after the water bearing fractures have been identified and the sampling zone can be isolated.

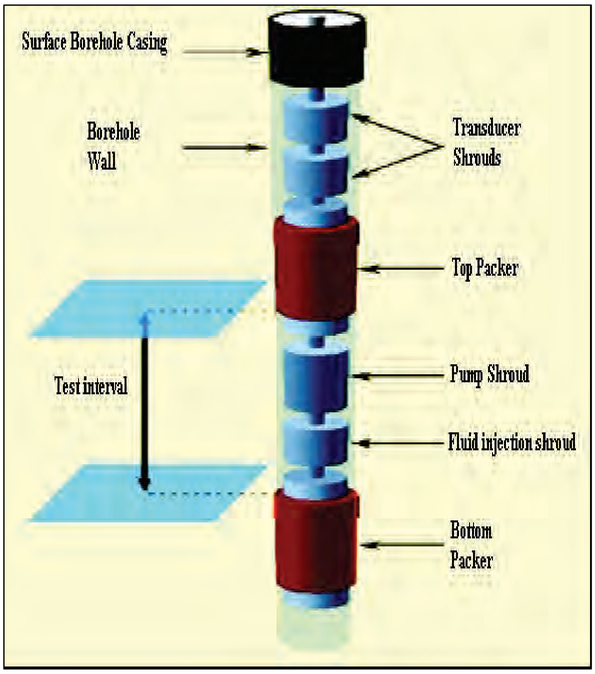


Figure 32: Multifunction BAT3 in a bedrock borehole with borehole packers inflated to seal against the borehole wall (from USGS, 2001)

This approach has been applied locally by Vogel et al. (1980) and Xu et al. (1998), without transducers, specifically for radioactivity. The success of the aforementioned method has unfortunately not been reproduced. Applicability of methodology to local conditions should be noted and this will definitely improve the quality of data stemming from fractured rock aquifers.

7.2.3 Depth specific passive samplers

In many cases in fractured rock aquifers, borehole yields are controlled by a water carrying single bedding plane fracture or a set of fracture networks. For Karoo sediments, sandstone is more permeable than mudstone, which is often embedded with each other. Under these hydrogeological conditions, depth specific samplers are proposed as a viable sampling option (Weaver et al., 2007). These are lowered into the borehole in order to gain a sample at the fracture or other area of interest. Unfortunately this method could artificially elevate turbidity in the well or borehole due to it disturbing the water while it is submerged (Parker and Mulherin, 2007). For this reason the Snap sampler™ has been developed. It is a passive sampling method allowing depth specific sampling of groundwater over a period of time. The sampler is left in the well in order to allow for equilibration after the initial disturbance caused by the insertion of the device into the well (Parker and Mulherin, 2007).This is especially useful in fractured rocks due to the fact that these conduits are the preferred paths of flow (Cook, 2003). Thus the sample would be representative of the aquifer and the actual flow chemistry over a time period as opposed to a grab sample at a moment in time like other depth specific samplers.

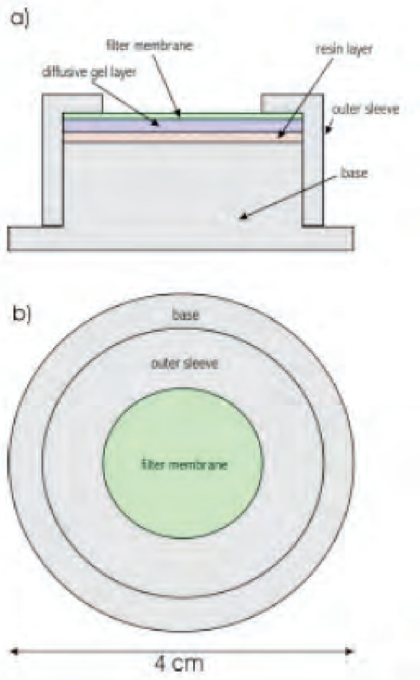


Figure 33: Schematic cross-section (a) and Plan view (b) of DGT sampler (INAP 2002).

Another useful sampling device is the DGT (Diffusive Gradient Thin Film). INAP (2002) outlines the use and applicability of this chelator type sampler. It works in a similar manner to the Snap sampler™ due to the fact that the sample taken is over a period of time and not at one specific moment as seen in Figure 33. Furthermore sample contamination is minimized and the sampler is easily deployed. Other advantages and disadvantages of the method are further mentioned by INAP (2002).

All of the aforementioned devices are viable sampling options for radioactivity in fractured rock aquifers. Care should be taken with regards to use and applicability and contamination. The choice of tool is dependent upon budget as well as availability of the equipment and the questions asked in the project.

7.3 Field determinants

Many groundwater chemical parameters have to be analyzed in a laboratory, but some parameters like temperature, pH, EC, etc., are best measured in the field for the following reasons:

- to check the efficiency of purging

- to obtain reliable values of those determinants that will change in the bottles during transport to the laboratory
- to obtain some values that may be needed to decide on the procedure or sampling sequence immediately during the sampling run

The above-listed reasons are also confirmed locally (Weaver et al., 2007). Based on local experience, this data collection in field can be accomplished by making use of a multi-parameter sonde.

It has also been suggested that radioactively contaminated groundwater with the exception of radon should be sampled using similar a methodology as that used for heavy metals (Wilde et al., 1998; Smedley et al., 2006; Weaver et al., 2007). This would entail the filtering of the sample, once it has been extracted from the aquifer (Levin, 1983). Typically a 0.45μm filter paper is utilized, in order to differentiate between dissolved and non-dissolved species (Yeskis and Zavala, 2002). Levin (1983) also suggests that the filter paper should be kept, if the suspended particles are to be analyzed. This is important, taking into consideration that Radium precipitates under oxidizing conditions. Despite all of this, liaising with the laboratory is critical to understand their needs for the analysis.

7.3.1 Borehole details

Any groundwater survey has as its base the collection of basic borehole details.

- **Borehole position** should be ascertained as accurate as is required. Standard GPS data are usually sufficient. In certain small scale investigations higher precisions may be required. The locations of nearby structures are also useful as reference points and to be able to judge influences when evaluating data later.
- **Groundwater level** is essential in order to assess flow possibilities and for comparison to later changes. The precision with which this is measured depends on the case at hand. In many cases where boreholes are already fully equipped, this is not possible.
- **Collar elevation** is a nice-to-have piece of data. Surveyed data are the best one can expect. Some GPS units are able, after suitable calibration to provide elevations, which may, or may not be, good enough for the task at hand. In the absence of these aids, the best one can do is to indicate the relative collar heights of the different boreholes, if they are visible.
- **Pumping equipment and flow conditions** should be recorded in order to evaluate the data later. A photograph of the borehole head is also a useful record. Do ensure that photos are properly labelled and that the clocks on cameras watches and other equipment are synchronised.

7.3.2 Parameters

Temperature

Ilani et al. (2005) have shown how the temperature in groundwater, in conjunction with reducing conditions, could increase the radium content. On the other hand most of the economically viable uranium deposits have formed under similar conditions (Ivanovich and Harmon, 1983). Thus one can see that the temperature of the water is a major determining factor for the type of radio nuclide. The radioactive decay of these radio nuclides releases heat, thus increasing the surrounding temperature. It is also important to note that the temperature logging of a borehole, in conjunction with other parameters, could act as an indicator of flow and therefore fractures within the subsurface.

The digital thermometer, which is quite accurate, has been proposed as the equipment of choice (Weaver et al., 2007). The use of mercury thermometers has been discouraged (Wilde et al., 1998). This is due to the health hazards which are associated with the heavy metal. Digital thermometers are usually incorporated into a pH meter, thus simplifying matters and one tool is transported instead of many. The meter should also be checked for batteries as well as calibrated according to manufacturer's instructions, on a regular basis (Levin, 1983).

Electrical Conductivity (EC)

The electrical conductivity (or EC) of water depends upon the presence of ions, their total concentration, mobility, valence, and relative concentrations, and on the temperature of groundwater when a measurement takes place (Weaver et al., 2007). In order to reduce the possibility of errors, Radtke et al. (2006) suggest that conductivity should be measured as close to the source as possible, using either a downhole or flowthrough-chamber sampling system. This principle of proximity should apply to all field parameters, irrespective of the method employed.

EC in conjunction with temperature has been used to characterize fractures in boreholes (Cook, 2003). Stepped values of EC are indicative of the inflow of water from another source into the borehole. Temperature can also be used (Weaver et al., 1999). Ivanovich and Harmon (1983) have also shown that the mobility of uranium is directly related to the presence and concentration of certain ions. Ilani et al. (2005) have shown that the radium content of groundwater is proportional to the chloride content in certain places. Thus there is a greater possibility for highly saline water to contain radium, rather than uranium. This would also be dependent upon whether there is any uranium bearing mineral in the flow path of the groundwater. Almeida et al. (2004) concur with the aforementioned facts and have also shown that there is a significant correlation between uranium concentration and electrical conductivity

pH

pH is defined as a(logarithmic) measure of the hydrogen ions concentration in water. It is defined as:

$$pH = -\log_{10} [H^+]$$

pH (together with Eh) is a major factor controlling the valence state, solubility and the mobility of trace metals (Weaver et al., 2007). Furthermore in conjunction with TDS, and specific ions, it could determine dominant species of these trace metals, such as uranium. Mudd (2002) has shown that the mobility of uranium, in groundwater greatly increases with a decrease in pH. This would explain the general increase in radioactivity observed in the vicinity of gold mines (Winde, 2004). This parameter should not be considered on its own, but rather in relation to other chemical measurements in order to gain a complete understanding of the hydrogeochemistry as involved in uranium speciation.

As all field equipment, pH meters should be calibrated on a regular basis and the instructions followed meticulously in order to obtain trustworthy results (Weaver et al., 2007).

Oxidation and reduction (Redox) potentials

Oxidation potential can be defined as the energy change, measured in volts, required adding or removing electrons, to or from an element or compound (Allaby and Allaby, 2003). Thus the redox potential, in conjunction with pH, dictates which ionic species would dominate within groundwater, or any water body for that matter. The radioactive isotopes of uranium are no exception to this rule. In mining activities the sulfides present are oxidized, thus leading to the acidification of the surrounding water and the release of metals. Acid Mine drainage (A.M.D), as it is commonly known, contains low levels of radioactivity when compared to nuclear waste. The mobility of uranium is largely controlled by Eh, pH and complex ions.

Eh is a measure of the equilibrium potential relative to the standard hydrogen electrode, developed at the interface between a noble metal electrode, usually platinum, and an aqueous solution containing electroactive redox species (Nordstrom and Wilde, 2005). The unit for measurement is millivolts (mV). The Eh meter can be incorporated into a pH meter, thus lightening the load for field trips. Nordstrom and Wilde (2005) and Weaver et al. (2007) extensively describe the methods and procedures relating to measurements as well as maintenance of the Eh meter.

7.3.3 Field Instrumentation

Reliable data collection in the field is a critical step of the proposed protocol. The in-situ determinants include parameters like temperature, pH, EC, etc., are best measured using a combination instrument. Depending on the choice of sensors all of these parameters can be analysed with the same instrument. Do ensure that switching between sensors does not change the calibration of each sensor. Even when storage of the measurement result in the instrument is available, do record the results elsewhere at the same time: they still could get lost.

In those cases where water is delivered by a pumping system, it is advisable to use a through flow cell to host the analytical sensors. The cell allows water to flow around all the sensors without atmospheric influence (Weaver et al., 2007). It is ideal for monitoring water quality during purging operations.

For down-hole logging (profiling) an instrument like the YSI 6600 multi-parameter instrument can be used. It is designed for long-term in situ monitoring and profiling of many parameters and can be deployed to 200 meters.

7.4 Laboratory determinations

The bulk of the data will be obtained from laboratory analyses. For all hydrochemistry and especially for radionuclide analyses, it is essential to find a good and reliable laboratory that can deliver results of the right quality, at the right price and within the right time. Do ensure that the requirements of the laboratory in terms of sample size, sample containers, storage and transport are carried out. Some techniques require that the laboratory be ready for analyses and that travel time be as short as possible. This should be arranged beforehand and some alternative arrangements can be and should anything go wrong. More information about these matters is given in Weaver et al. (2007).

8. MONITORING PROTOCOL

Groundwater monitoring is the scientifically-designed, near continuous/regular measurement and observation of the groundwater situation (Jousma and Roelofsen, 2003). The design of the network density and sampling frequency should be based on an optimization between the cost of monitoring, of the accuracy of collected and derived data related to the objectives of the network (Kovalevsky et al., 2004) and the cost of doing it wrong. Groundwater monitoring sites should be selected so as to be representative of geographic distribution, geology, groundwater use, land-use and groundwater flow regimes amongst other factors. The main aim is to design the programme so that the required questions will be addressed by the likely outcome.

Titus and Hohne (2007) have examined the development of a radioactivity monitoring program for groundwater. The goals of the program would be:

- National scale monitoring: Long-term, standardized measurements and observations of groundwater and in order to define status and trends of groundwater resources to determine its "fitness of use".

- Local scale monitoring: Subsequent monitoring could also be (based on availability of funds and for a subsequent phase) of finite duration, intensive and site-specific in order to measure and observe the quality of groundwater resources in selected impacted groundwater sites in South Africa.

The proposed monitoring of the Beaufort West aquifer would be an example of local scale monitoring.

8.1 Preparation phase

8.1.1 Selection of monitoring boreholes

Decisions about the placement and construction of monitoring holes are among the most difficult in developing an effective monitoring program (Barcelona et al., 1985). Therefore it is important to understand the current flow regime and this is done by developing a conceptual model which utilizes the available data (Jousma, 2006).

Hunt (2007) argues that geostatistics, in conjunction with GIS, could be used as an effective tool for optimizing monitoring well location. In order to do this one would require a good set of data in the area. This is due to that fact that this statistical modelling is based on the assumption that there is a relationship between samples according to their position and their relationships with their neighbours (Clark, 1987).

The semi variogram is utilized for this purpose and works on the aforementioned premise of correlation among samples due to distance. The semi-variogram is determined as follows (Zhou, 1992):

- Several groups (m) of distances between measurement locations with an average distance d are defined. For example, d_1 is the group where the distances between the locations are small, whereas d_m is the group with the largest distances;
- For each distance group d_k the possible pairs of measurements locations i and j are identified (n_k: all possible pairs);

For each distance group d_k the variogram value (d_k) is calculated using the following equation:

$$\gamma(d_k) = \frac{1}{2n_k} \sum_{1}^{k} (Z_i - Z_j)$$

where Z_i and Z_j are the measured variables at locations i and j. This could be the amount of radon in groundwater or some other concentration of an element. The process is repeated at varying distances (Hunt, 2007). Finally these values are plotted onto an experimental semi-variogram.

This semi variogram forms the basis for a spatial interpolation technique known as kriging. The area of interest is then covered by a grid and each block within the grid is filled by an estimated value determined by the kriging process. This is usually done with a software suite and a 'smoothed out' picture is given for the location of the elements at hand. After all the calculations three layers are projected, namely:

- Number of samples
- Kriging efficiency map
- Geoscientific knowledge

Finally a combination of all the above layers leads to the highlighting of areas which require additional sampling (Hunt, 2007). This fourth and final layer is the one which is used in order to maximize the location of future monitoring wells. This method takes into consideration the possible heterogeneities of the subsurface by including the layer with geoscientific knowledge. In the aforementioned layer one could possibly include features affecting groundwater flow, such as lineaments and dykes (Cook, 2003). Another possibility could be the inclusion of the ore body. This method in conjunction with geo-statistics seems to be the best option for maximizing monitoring well location.

Unfortunately this type of modelling also has its downfalls. Problems with Kriging arise in the initial stages of the assumptions. Firstly, true variance of the single distance-weighted average is replaced with the false variance of a set of distance-weighted averages (Mercks, unpub). Also flow in fractured rock aquifers is quite heterogenous and modelling this process is quite complex

(Cook, 2003). As we all know all models contain errors but some are useful. Therefore despite the fact that it is based on many assumptions, it is still a qualitative method.

8.1.2 Sampling frequency

The main objective of sampling frequency, flow times, fracture connectivity, water level fluctuations, and sampling interval needs to be properly defined to capture the overall response of the contamination plume, within the limited number of field measurements. Due to a lack of case studies in South Africa and experience in monitoring of contamination migration, overseas experience can be used as an initial guide.

EPA (1992) promotes the hourly sampling of fractured aquifers for field determinants. This protocol was developed specifically for nuclear waste facilities and the parameters which would be measured on an hourly basis would include those which a data logger could determine. These include temperature, TDS and water level. This would aid in determining whether leakage has occurred from the storage facility and also aid in determining anomalous inflows of contaminants in groundwater, in a natural setting. The aforementioned could be inferred from an increase in TDS, pH and temperature.

Kau (2006) has sampled for radon on an hourly basis. This continual sampling was done at a spring, located along a fault. The anomalous decrease in Radon proved to be an indicator for a major earthquake in the region (Kau et al., 2006). Monitoring of such a nature should only be implemented when a similar purpose and outcome is intended. Budgetary constraints would play a major role in deciding which geologically active areas require monitoring of such a nature in order to alleviate the possible impacts on human lives. A monitoring program like this would be subject to a similar set of constraints.

Durrani and Ilic (1997) have shown that a seasonal variation of Radon occurs in the subsurface. This could be attributed to the increased moisture during the wet season, thus trapping the Radon in the groundwater. In the dry season the soil moisture content is not as high and thus the soil is more aerated. Therefore the radon gas is able to rise through the available pore spaces and escape into the atmosphere (Figure 34). Radon monitoring therefore requires very regular sampling in order to identify a signal above the normal seasonal variation. According to Durrani and Ilic (1997) it would be advisable to sample twice annually, once after the wet season and again after the dry season, but this will entirely depend on the signal size expected from the system.

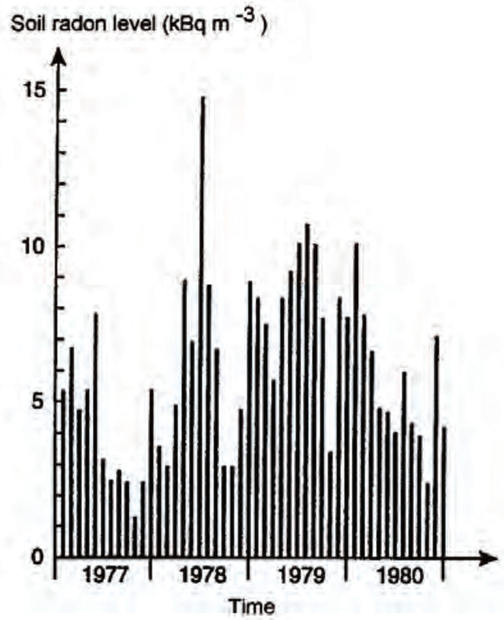


Figure 34: Seasonal variation of Radon occurrence in soil (Durrani and llic, 1997).

A statistical analysis could also be done in order to effectively ascertain sampling frequency. This would mean that a substantial amount of data would be required and it would have to stem from the area of interest. As a crude guideline one needs about five samples from a groundwater source with seasonal variation to indicate variability (Weight and Sonderegger, 2000). The step trend which emerges in Figure 34 is one of the types of patterns which could possibly occur. The purpose of trend analysis, in statistical terms, is to determine whether the probability distribution from a series of observations has changed over time (Helsel and Hirsch, 2002). The simplest statistical method which could be used to ascertain this variability would have to be based on historical data (Kovalevsky et al., 2004). Furthermore it could also be said that the monitoring program would have to take cognizance of background levels prior to human impact, as well as adjust the monitoring program in order to account for the increased variability introduced by human impact (Kovalevsky et al., 2004).

As discussed before, the main recharge in Beaufort West would definitely come from the north and west (Gamka River, Platdoring River) during the flood season, and lateral recharge in the vicinity of dolerite dykes. Though this project could not find unequivocal evidence to substantiate that claim, it is cautious to do monitoring twice a year and once immediately after floods. This recommendation is far from final as it should be reviewed after a period of five years.

8.1.3 Selection of sampling parameters

Since the objectives of the monitoring phase are basically to answering very specific questions, it is possible to reduce cost by only analysing a limited number of parameters. Some balance has to be struck between the temptation to analyse many parameters as against the cost of the actual field work involved. For instance, if in Beaufort West the main question is whether there is contamination of the aquifers with uranium and its daughters, then these are the parameters that need to be analysed. If there are certain proxies available that are cheaper or easier to sample, for example gross alpha and beta, then that can be explored.

8.2 Execution of the monitoring phase

The work involved with the monitoring phase is very similar to actual sampling as described earlier. Since this might well become routine (especially when short time intervals are involved) one runs the danger that certain steps are neglected with time. It is therefore necessary that the supervisor exerts occasion quality checks. Errors that can creep in is that samples get mixed up, bottles are not labelled properly, purging times are shortened, etc. The supervisor must therefore establish checking procedures and ensure that the sampling staff is aware that checks will be made.

On receipt of analytical results, a procedure must be available whereby the new data are checked for internal consistency and compared with earlier data. This will show up instances of some of the above errors occurring and check whether there is a change in some parameters: this is actually the object of the whole exercise. While there are software methods to accumulate results and flash warnings when certain levels are exceeded, a simple graph against the wall, will be just as good.

If there appear to be discrepancies, these must be evaluated. If there is doubt about an analysis results, by all means ask the lab to confirm the result. If no reasonable explanation is obtained, then immediate resampling is called for. This will show whether there is a real event occurring, or not. This may lead to a decision to increase the sample frequency to follow the event, or else to launch a full-scale re-evaluation.

8.3 A flow chart for the monitoring process

The steps outlined in the two chapters on sampling and monitoring have been summarised in the form of a flow chart (Figure 35).

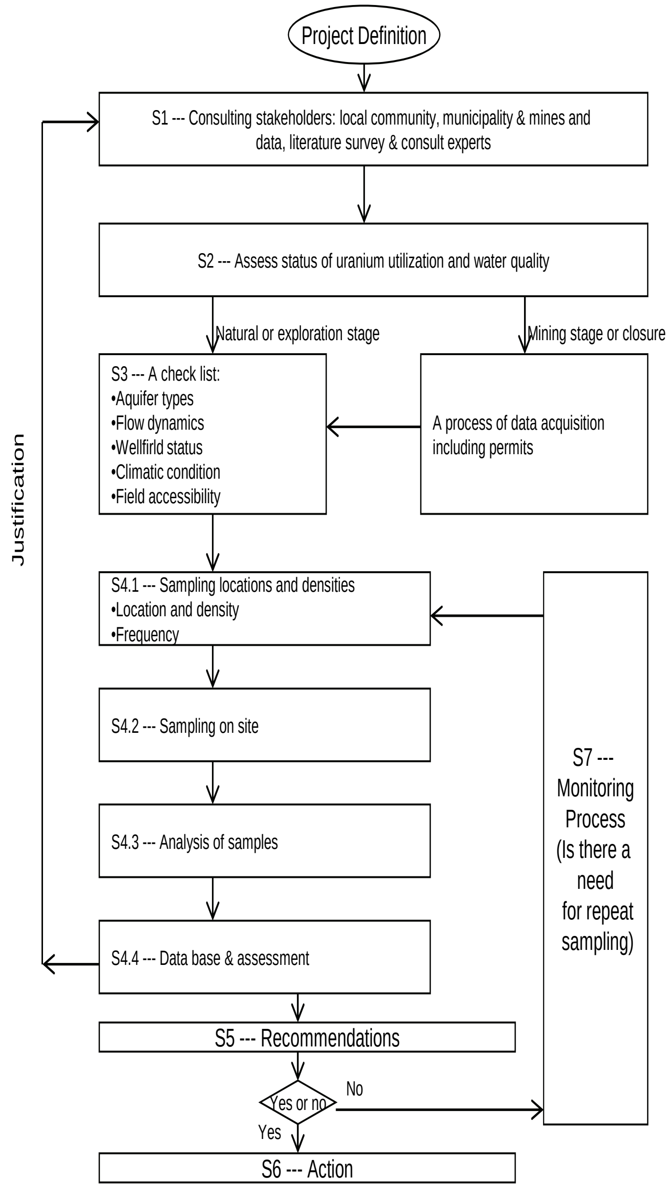


Figure 35: Functional flow chart when carrying out sampling and monitoring.

8.4 A monitoring programme for Beaufort West

Using the above concepts and the data from the Beaufort West wellfields, it is now possible to develop a monitoring programme to warn about possible uranium inflows into these wellfields. It is suggested that a monitoring programme be established and implemented in consultation with the local municipality wellfield managers.

Firstly representatives of monitoring sites should be selected. Based on the summer rain climatic condition, three samples per site may be taken, namely, early rain season in October ~December of a year, peak rain season in March~April and the dry season in May~July/September. In case of a big flooding event, it is always cautious to do check-up monitoring immediately after the floods. A functional flow chart as shown in Figure 35 should be adhered to when a monitoring programme is implemented.

9. IMPLEMENTATION OF A MONITORING PROTOCOL

From increased understanding of local hydrogeology to adopt methods for groundwater protection, two types of approaches are appealing to us, i.e. rudimental distance and numeric methods.

As groundwater becomes increasingly important in Beaufort West, protection and preservation of groundwater resources should be seen as a priority in water supply strategy. But how to implement such a protection deserve much discussion. Two critical issues are discussed here from angles of (1) availability of data and (2) technical capacity.

9.1 Technical feasibility

Advantage versus disadvantage of use rudimental distance and numeric methods. The feasibility document on protection zoning (DWAF, 2008) identifies various implementation steps for zoning. These range from highly technical steps to addressing social issues and post zone delineation monitoring and evaluation. These steps are:

- Stakeholder involvement and public awareness
- Aquifer characterization
- Risk Assessment and identification
- Zonal delineation
- Data management
- Post delineation monitoring and assessment

Despite the South African government having recognized the importance of such a policy this project still remains at the feasibility stage to date.

Hindering factors prove many. Even though South Africa has been exploring the option of implementing a zoning policy it is very likely that there are several factors that might hinder the successful implementation of such a policy and the end result will be a phased implementation of the policy based on how well the issues affecting the implementation factors mentioned above are addressed. Some of the issues are addressed below.

Socio-economic Impacts: One also needs to assess the socio-economic impact of restricting activities around water resources. It is often the case that many of the very activities that sustain rural and poorer communities occur on land within the protection zone. In delineating the zones a balance needs to be maintained between resource protection and socio-economic development. Placing large portions of land under land constraints might lead to resistance from communities as the perceived loss of income generated from the land will supersede the importance of a safer water source. This resistance due to perceived loss of income could possibly be eliminated by monetary compensation for the loss of agricultural production from the zoned land.

Stakeholder Collaboration: It is important that an extensive public participation and education programme be held before implementing such a policy. Stakeholder support is vital to a zoning policy being successful as zoning actually restricts future land uses and may impose onerous obligations on the current land users/owners.

Lack of Technical Capacity: The lack of sufficient local and technical knowledge and capacity in contaminant travel characteristics within the specific fractured rock aquifers present on the African continent are also factors in hindering implementation of groundwater protection zones. Capacity building in sub-Saharan Africa in regards to technically skilled groundwater professionals is urgently required (Kreamer and Usher, 2010; Robins et al., 2007)

Lack of Sufficient Data: Zoning as described in Nel et al., 2009 seems to be quite a data intensive activity. Currently there appears to be a huge gap in data across the sub-Saharan continent in regards to groundwater (Kreamer and Usher, 2010). This data is pertinent for one to conduct risk assessments, vulnerability mapping and delineation of the zones. It is likely that in South Africa that sufficient data may exist for such assessments, however much of the data has not been captured electronically on the proper databases (Kreamer and Usher, 2010).

Scale of Groundwater Development: Many socially important aquifers are often lower yielding single boreholes rather than high yielding wellfields (Robins et al., 2007). It is the rural low yielding yet socially important resources units that require greater levels of protection as it is often the case that water from these resources are consumed without any prior treatment unlike municipal well fields which undergo treatment and purification if required. Also in terms of the high volume of low yielding rural boreholes compared to the smaller number of higher yielding municipal wellfields, delineating zones around the rural boreholes may prove more time consuming and difficult.

Levels of legal framework development: Across the sub-Saharan continent there are different levels of legal development. There may be little or no legal instruments for groundwater protection versus there are such instruments but they are toothless and hence cannot be implemented in practice. Generally within most sub-Saharan countries very little legal instruments exists to enforce such a strategy. However even though South Africa is moving towards policy formulation, they are still struggling on the ground level to enforce these laws. This may be as a consequence of understaffing, lack of appropriate technical skills, lack of institutional structures or/and lack of appropriate funding. Enforcement may also be difficult since the NWA has been fashioned around legislation from various developed countries but the reality is that conditions in SA are still developing world. It is quite evident in South Africa that whilst the legislation is in place to address protection of groundwater resources, the policies to effect this protection often lags behind the legislative framework.

Lack of sectoral integration: Another important hindering factor would be the lack of sectoral integration of water resources management including groundwater cross the Africa, even though many great initiatives are on the table, namely river basin organization, Lake organization, etc.

With the newly establishment of AMCOW Groundwater Commission, the situation would be rectified in the manner that groundwater as a basic guarantee for water security in vast rural Africa can be realized.

To guarantee a good quality water supply entails effort in many aspects ranging from borehole siting, borehole construction and pump installation to demarcation of protection zones around boreholes or wellfields. Though protection zoning around a well or borehole is widely practised in some developed countries, it proved difficult in their adoption locally in South Africa, especially in other African countries. Taking into account the developing nature of socio-economic infrastructures in Beaufort West, this report maintains that measures of sanitary seal and simple minimum distance (or safe distance) separating the wellfield from pollution sources are still first defence measures against well / borehole contamination for Africa (Xu and Braune, 1995; Lawrence et al., 2001; Rajkumar and Xu, 2011).

9.2 Socio-economic, political and institutional issues

Water in South Africa is a public good that needs to be conserved and protected to meet the needs of current and future users. With emerging scientific and public awareness of the potential for detrimental health effects due to the accumulation of hazardous compounds in the various environmental media such as soil, groundwater, surface water and air, efforts to restore the natural environmental media to acceptable conditions are of benefit to society as a whole.

Over the last two decades, much evidence has surfaced to indicate that the water resources of South Africa, a public good, are threatened by contamination caused by historical and present industrial, agricultural, and commercial activities. The response of the South African public to this growing perception of threatened water resources, with uncertainty surrounding the risks to human health and water-dependent ecology, has generally been to demand the restoration of the resource to safe and acceptable water for drinking and other purposes. This particular public clamour is an expression of a right enshrined in the Constitution of South Africa, the supreme law of the country (Constitution, 1996), and is entrenched in current water law in the National Water Act (Act No. 36 of 1998) (National Water Act, 1998), and water policy (statements of intent) (de Coning, 2006). The constitutional mandate relating to water affords and assures every person a fundamental right to an environment that is not harmful to his or her well-being, and requires that the environment be protected for the benefit of present and future generations. Such protection of water resources should be provided through reasonable legislation and other measures that safeguard ecologically sustainable development and use of water resources, while promoting justifiable economic and social development (Constitution, 1996).

The National Water Act (Act No. 36 of 1998) ("NWA") provides for fundamental reform of the law relating to water resources in South Africa. The preamble of the Act, amongst others:

- recognises that water is a scarce resource and is an unevenly distributed national resource that occurs in many different forms, which are all part of a unitary, inter-dependant cycle;

- recognises that water is a natural resource belonging to all people. Past discriminatory laws and practices have prevented equal access to water, and the use of water resources;
- acknowledges the National Government's overall responsibility for, and authority over, the nation's water resources and their use, including the equitable allocation of water for beneficial use, the redistribution of water, and international water matters;
- recognises that the supreme aim of water resource management is to achieve sustainable use of the water for the optimal benefit of all users;
- recognises that the protection of the quality of water resources is necessary to ensure sustainability of the nation's water resources in the wider interest of all users of water, including future generations; and
- recognises the need for the integrated management of all aspects of water resources and, where appropriate, the delegation of management functions and authority to a regional or catchment level in order to allow all to participate.

Therefore groundwater protection zoning plays a key role in setting priorities for groundwater quality monitoring and pollution control. All of these activities are essential components of a sustainable strategy for groundwater quality protection and will minimise impacts on the environment, which is one of the cornerstones of the National Water Act (Act No. 36 of 1998).

Provision of safe drinking water to any community is of utmost importance. In rural Africa, the problems surrounding provision of water for basic human needs are numerous from supply to quality. Groundwater is the most logical choice in most rural areas, though one needs to take into cognisance all the potential problems as highlighted in this paper, especially in terms of microbiological pollution. In order to provide a reliable service of clean safe water, African groundwater practitioners need to address various issues:

First and foremost, groundwater developers should ensure that groundwater resources have the appropriate sanitary seals and wellhead protection mechanisms as well as boreholes are sited hydraulically upgradient of point pollution sources. Deeper aquifers with well-constructed boreholes (appropriate casing lengths and sanitary seals) should be investigated. As can be seen from the UNEP-UNESCO led project (Xu and Usher, 2006), many of the shallow easily accessible aquifers are already polluted and an alternative needs to be investigated.

Knowledge on the state of groundwater is minimal in most African countries. Complete surveys and hydro census needs to be conducted to establish baseline technical data on existing infrastructure (groundwater usage, well construction, pollution issues, water resource potential). Once conducted, the data can be utilized to determine aquifer pollution vulnerability and subsurface contaminant loads. Pending these assessments protection measures can be prioritized and initiated.

Many countries need to increase focus on groundwater monitoring programmes for both quantitative and qualitative data, with more specification on microbiological qualitative monitoring to be carried out. This will help paint a clearer picture of the state of resources and help with planning of protection measures. Not enough microbial monitoring data are available allowing, characterization of microbial quality trends.

Leading from this, appropriate management plans specific to socially important and productive wellfields should to be drawn up. A well managed and routine system helps in identification of problems before they become detrimental.

The current geo-technical skills shortage within the African continent is another factor that needs to be urgently addressed. Africa's hard rock aquifers are complex in terms of understanding contaminant transport. In order to fully understand groundwater and contaminant movement in a dual porosity system one requires sophisticated and well planned experiments which are usually expensive to conduct and require highly technical skilled people.

Also changing and improving of on-site sanitation technologies would greatly assist in minimizing risk to pollution of groundwater resources. Whilst the urine diversion system is the more expensive option as compared to pit latrines and VIP systems, it can be seen that in the longer term the environmental and health benefits far outweigh the initial higher cost implication (Von munch and Mayumbelo, 2007).

The results from the UNEP-UNESCO led project (Xu and Usher, 2006), suggest that land use constraints as required in zoning can be technically justified, but will require refinement of exact delineation areas for high loading microbiological contaminant sources. The study also highlights the need for integrated land-use planning and geotechnical mapping in order to minimize contamination and better protect groundwater resources as expansion of the metropolitan area occurs.

At a final and most advanced level, the application of land use constraints around water resources must occur in conjunction with a public participation program which creates awareness around water quality issues with local communities. This should take into account socio-economic impacts on communities, environmental, health and service delivery issues as well.

10. CONCLUSION AND RECOMMENDATIONS

In this report much consideration was given to potential uranium contamination in groundwater and protection for municipal abstraction. Groundwater abstraction for irrigation and wind-pumps has been ignored. The abstraction from wind-pumps for stock watering and domestic purposes are less meaningful in the context of protection on the ground that (1) wind-pump abstraction is negligible in comparison with irrigation abstraction, (2) wind-pump abstraction is unlikely to change dramatically from year to year, and (3) it is very difficult to obtain a realistic value for the quantities abstracted anyway.

Based on the above-discussed, the following is recommended:

- No evidence of the uranium contamination was found in Beaufort West during the project. As the duration of the project is relative limited, no sufficient database is available to categorically state that groundwater in Beaufort West will not be contaminated by the uranium in future. The proposed monitoring for the Beaufort West should be implemented with data to be captured into relevant DWA database for evaluation and protection for groundwater security.
- The proposed sampling and monitoring of the uranium in groundwater should be further tested through more case studies.

It is further proposed that the monitoring activity in Beaufort West be incorporated into a Water Safety Plan (WSP). WSP is proactive risk-based approach (Breach et al., 2011; Foster et al., 2002). The approach considers the safety of drinking water supplies through the use of a comprehensive risk assessment and risk management approach that encompasses all steps in water supply from catchment to consumer. SWP is underpinned by the so-called multi barrier approach, which is based on having in place a number of separate barriers to hazards that may be present in raw water. This means that if one barrier fails for any reason then the other barriers can still prevent or minimize contamination of the final water supplied to consumers. The multi barrier approach can cover all aspects of water quality management including catchment protection, water treatment, and management of the distribution network. However, protection of raw water sources should be seen as the first and sometimes the most important barrier to prevent microbial and / or chemical contamination of drinking water. This is particular true for all types of groundwater water supply sources. In addition to strategies for control of groundwater pollution, mapping overall groundwater pollution vulnerability and assessing subsurface pollution load and restriction of potentially polluting activities, our emphasis is placed here on groundwater source protection areas.

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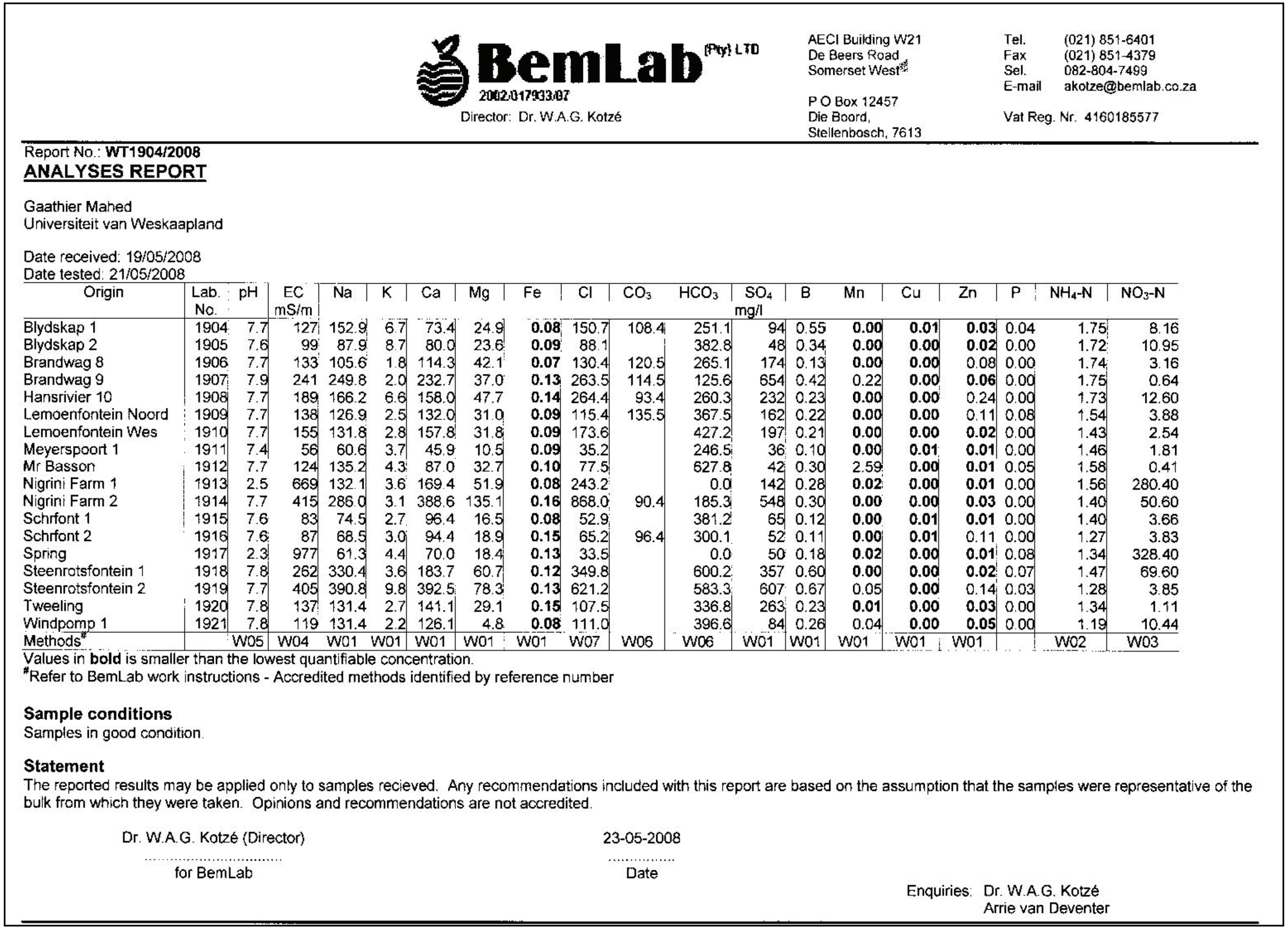
12. APPENDIX A: CHEMISTRY DATA

Table 9: Laboratory results (May 2008 hydrocensus).



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Report No.: **WT1904/2008**

ANALYSES REPORT

Gaathier Mahed
Universiteit van Weskaapland

Date received: 19/05/2008
Date tested: 21/05/2008

Origin	Lab. No.	pH	EC mS/m	Na	K	Ca	Mg	Fe	Cl	CO_3	HCO_3	SO_4 mg/l	B	Mn	Cu	Zn	P	NH_4-N	NO_3-N
Blydskap 1	1904	7.7	127	152.9	6.7	73.4	24.9	**0.08**	150.7	108.4	251.1	94	0.55	**0.00**	**0.01**	**0.03**	0.04	1.75	8.16
Blydskap 2	1905	7.6	99	87.9	8.7	80.0	23.6	**0.09**	88.1		382.8	48	0.34	**0.00**	**0.00**	**0.02**	0.00	1.72	10.95
Brandwag 8	1906	7.7	133	105.6	1.8	114.3	42.1	**0.07**	130.4	120.5	265.1	174	0.13	**0.00**	**0.00**	0.08	0.00	1.74	3.16
Brandwag 9	1907	7.9	241	249.8	2.0	232.7	37.0	**0.13**	263.5	114.5	125.6	654	0.42	0.22	**0.00**	**0.06**	0.00	1.75	0.64
Hansrivier 10	1908	7.7	189	166.2	6.6	158.0	47.7	**0.14**	264.4	93.4	260.3	232	0.23	**0.00**	**0.00**	0.24	0.00	1.73	12.60
Lemoenfontein Noord	1909	7.7	138	126.9	2.5	132.0	31.0	**0.09**	115.4	135.5	367.5	162	0.22	**0.00**	**0.00**	0.11	0.08	1.54	3.88
Lemoenfontein Wes	1910	7.7	155	131.8	2.8	157.8	31.8	**0.09**	173.6		427.2	197	0.21	**0.00**	**0.00**	**0.02**	0.00	1.43	2.54
Meyerspoort 1	1911	7.4	56	60.6	3.7	45.9	10.5	**0.09**	35.2		246.5	36	0.10	**0.00**	**0.01**	**0.01**	0.00	1.46	1.81
Mr Basson	1912	7.7	124	135.2	4.3	87.0	32.7	**0.10**	77.5		627.8	42	0.30	2.59	**0.00**	**0.01**	0.05	1.58	0.41
Nigrini Farm 1	1913	2.5	669	132.1	3.6	169.4	51.9	**0.08**	243.2		0.0	142	0.28	**0.02**	**0.00**	**0.01**	0.00	1.56	280.40
Nigrini Farm 2	1914	7.7	415	286.0	3.1	388.6	135.1	**0.16**	868.0	90.4	185.3	548	0.30	**0.00**	**0.00**	**0.03**	0.00	1.40	50.60
Schrfont 1	1915	7.6	83	74.5	2.7	96.4	16.5	**0.08**	52.9		381.2	65	0.12	**0.00**	**0.01**	**0.01**	0.00	1.40	3.66
Schrfont 2	1916	7.6	87	68.5	3.0	94.4	18.9	**0.15**	65.2	96.4	300.1	52	0.11	**0.00**	**0.01**	0.11	0.00	1.27	3.83
Spring	1917	2.3	977	61.3	4.4	70.0	18.4	**0.13**	33.5		0.0	50	0.18	**0.02**	**0.00**	**0.01**	0.08	1.34	328.40
Steenrotsfontein 1	1918	7.8	262	330.4	3.6	183.7	60.7	**0.12**	349.8		600.2	357	0.60	**0.00**	**0.00**	**0.02**	0.07	1.47	69.60
Steenrotsfontein 2	1919	7.7	405	390.8	9.8	392.5	78.3	**0.13**	621.2		583.3	607	0.67	0.05	**0.00**	0.14	0.03	1.28	3.85
Tweeling	1920	7.8	137	131.4	2.7	141.1	29.1	**0.15**	107.5		336.8	263	0.23	**0.01**	**0.00**	**0.03**	0.00	1.34	1.11
Windpomp 1	1921	7.8	119	131.4	2.2	126.1	4.8	**0.08**	111.0		396.6	84	0.26	0.04	**0.00**	**0.05**	0.00	1.19	10.44
Methods#		W05	W04	W01	W01	W01	W01	W01	W07	W06	W06	W01	W01	W01	W01	W01		W02	W03

Values in **bold** is smaller than the lowest quantifiable concentration.
#Refer to BemLab work instructions - Accredited methods identified by reference number

Sample conditions
Samples in good condition.

Statement
The reported results may be applied only to samples recieved. Any recommendations included with this report are based on the assumption that the samples were representative of the bulk from which they were taken. Opinions and recommendations are not accredited.

Dr. W.A.G. Kotzé (Director)
....
for BemLab

23-05-2008
....
Date

Enquiries: Dr. W.A.G. Kotzé
Arrie van Deventer

Table 10: Chemistry database.

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO4 mg/l	N NO3mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	N_Amonia mg/l
G29858B	05/04/2006	7.6	125	800	105	35	107	0.9	264	134	172	-1	-1	-1	0	0	-1
G29858B	21/05/2008	7.7	133	-1	114.3	42.1	105.6	1.8	385.6	130.4	174	3.16	-1	-1	0.07	0	1.74
G29858F	30/06/1997	7.4	141	902	126	31.6	136	2.1	213	138	570.6	1.3	0.8	0.04	-1	0	-1
G29858KA	30/06/1997	7.4	160	1024	146	35.6	145	2.5	234	193	623.2	0.7	0.8	0	-1	0.01	-1
G29858KA	05/04/2006	7.5	170	1088	160	33	156	2.4	247	200	326	-1	-1	-1	0	<0.05	-1
G29858O	30/06/1997	7.9	100	640	69.4	27.3	109	0.9	304	71	201.6	0.6	1.1	0	-1	0	-1
G29858P	30/06/1997	7.5	149	954	140	47.1	108	1.3	295	184	375.3	4.5	0.5	0	-1	0	-1
G29858V	30/06/1997	7.7	126	806	96.5	20.6	156	1.2	219	87	561	0.09	1	0	-1	0.07	-1
G29858V	05/04/2006	7.3	250	1600	247	52	244	2.4	206	307	708	-1	-1	-1	0.13	0.17	-1
G29858V	22/11/2006	7.6	275	-1	269	51	272	1.9	168	226	1011	0	0.96	-1	-1	-1	-1
G29858V	21/05/2008	7.9	241	-1	232.7	37	249.8	2	240.1	263.5	654	0.64	-1	-1	0.13	0.22	1.75
G29859C	30/06/1997	7.2	170	1088	153	65.7	118	1.2	337	211	480.5	5.1	0.5	0.02	-1	0.01	-1
G29859C	22/11/2006	7.7	150	-1	135	54	102	1.4	352	152	193	4.6	0.56	-1	-1	-1	-1
G29872D	30/06/1997	7.5	160	1024	146	58.8	121	1.6	349	183	430.5	7.1	0.5	0	-1	0	-1
G29879BC	30/06/1997	7.1	130	832	97.6	36.6	140	2.6	280	146	355.3	4.6	0.6	0	-1	0	-1
G29879BC	05/04/2006	7.5	144	922	128	30	148	2.6	339	125	219	-1	-1	-1	0.06	<0.05	-1
G29879BC	23/11/2006	7.7	143	-1	123	32	127	2.5	347	124	180	3.8	0.93	-1	-1	-1	-1
G29879BC	21/05/2008	7.7	138	-1	132	31	126.9	2.5	503	115.4	162	3.88	-1	-1	0.09	0	1.54
G29894L	30/06/1997	7.8	123	787	100	32.1	118	2.2	240	150	322.3	0.3	0.4	0	-1	0	-1
G29894L	05/04/2006	7.6	130	832	116	26	124	2.1	233	139	209	-1	-1	-1	0	0	-1
G29894L	22/11/2006	7.8	130	-1	112	28	121	1.6	239	139	196	0.52	0.52	-1	-1	-1	-1
G29896K	30/06/1997	7.6	144	922	140	27.7	124	1.5	230	207	352.3	0.09	0.3	0	-1	0	-1
G29914A	30/06/1997	7.5	84	538	55.5	25.9	84	8.3	283	62	447.7	5.5	0.4	0	-1	2.72	-1
G33542	30/06/1997	7.5	154	986	137	42.7	123	1	242	242	378.7	0.09	0.6	0	-1	0	-1
G33544	30/06/1997	7.6	90	576	92.6	8.1	91	2	213	49	286.4	2	1.1	0	-1	0	-1
LS1	21/05/2008	7.7	155	-1	157.8	31.8	131.8	2.8	427.2	173.6	197	2.54	-1	-1	0.09	0	1.43
Private1	30/06/1997	7.2	310	1984	274	123	227	2.1	306	610	974.9	2.7	0.7	0.01	-1	0	-1
Private2	30/06/1997	7.4	270	1728	243	101	201	1.9	287	511	580.2	2.5	0.7	0	-1	0	-1
Private2	05/04/2006	7.8	230	1472	224	66	203	1.8	248	297	533	-1	-1	-1	0	0	-1
Private2	22/11/2006	7.7	215	-1	184	63	177	2.2	235	309	460	1.4	0.76	-1	-1	-1	-1
SRK3	05/04/2006	7.5	180	1152	176	21	206	1.7	215	133	569	-1	-1	-1	0.27	0.13	-1
Noordeinde_Suid	05/04/2006	7.6	78	499	68	22	69	1.7	250	47	81	-1	-1	-1	0	0	-1
Noordeinde_Suid	09/08/2007	7.9	92		78	29	69	1.6	272	61	100	1.8	0.73	-1	-1	-1	0
Noordeinde_Suid	23/11/2006	7.4	77	-1	66	23	60	1.6	233	42	76	1.4	0.73	-1	-1	-1	-1
Noordeinde_Noord	23/11/2006	7.5	88	-1	78	25	69	1.5	257	49	103	2	0.71	-1	-1	-1	-1
Waterval	05/04/2006	7.5	89	570	129	11	54	1.1	240	14	214	-1	-1	-1	0.06	0.12	-1
Fontein	05/04/2006	7.4	90	576	127	10	55	0.9	241	15	217	-1	-1	-1	0	0.08	-1
Fontein	23/11/2006	7.3	51	-1	50	19	28	0.6	207	10	40	0	0.37	-1	-1	-1	-1

Volstruisgat	05/04/2006	7.5	87	557	82	23	68	1.2	247	47	129	-1	-1	-1	0	0	-1
G29947A	05/04/2006	7.6	72	461	79	21	44	1.1	211	17	141	-1	-1	-1	0	0	-1
G29877L_new	04/09/2007	7.3	232	-1	238	16.4	267.3	1.4	289.4	345.1	529	0	-1	-1	0.11	0.35	0
DR_5	16/05/2008	7.8	149	-1	152.3	33.1	93.6	3.5	261.8	198.3	146	13.16	-1	-1	0.06	0	0.32
HR_10	16/05/2008	7.7	194	-1	151.3	45	164.7	6.4	246.5	267	229	10.64	-1	-1	0.71	0.65	0
HR_10	21/05/2008	7.7	189	-1	158	47.7	166.2	6.6	353.7	264.4	232	12.6	-1	-1	0.14	0	1.73
HR_13	16/05/2008	7.8	195	-1	161.5	44.3	163.5	6.8	344.5	250.3	243	13.29	-1	-1	0.06	0.01	0.09
HK_NDA	16/05/2008	7.8	166	-1	120.8	32.3	179	2.9	338.4	195.6	218	7.64	-1	-1	0.01	0	0
Blydskap 1	21/05/2008	7.7	127	-1	73.4	24.9	152.9	6.7	359.5	150.7	94	8.16	-1	-1	0.08	0	1.75
Blydskap 2	21/05/2008	7.6	99	-1	80	23.6	87.9	8.7	382.8	88.1	48	10.95	-1	-1	0.09	0	1.72
Meyerspoort 1	21/05/2008	7.4	56	-1	45.9	10.5	60.6	3.7	246.5	35.2	36	1.81	-1	-1	0.09	0	1.46
Mr Basson	21/05/2008	7.7	124	-1	87	32.7	135.2	4.3	627.8	77.5	42	0.41	-1	-1	0.1	2.59	1.58
Nigrini Farm 1	21/05/2008	2.5	669	-1	169.4	51.9	132.1	3.6	0	243.2	142	280.4	-1	-1	0.08	0.02	1.56
Nigrini Farm 2	21/05/2008	7.7	415	-1	388.6	135.1	286	3.1	275.7	868	548	50.6	-1	-1	0.16	0	1.4
Schrfont 1	21/05/2008	7.6	83	-1	96.4	16.5	74.5	2.7	381.2	52.9	65	3.66	-1	-1	0.08	0	1.4
Schrfont 2	21/05/2008	7.6	87	-1	94.4	18.9	68.5	3	396.5	65.2	52	3.83	-1	-1	0.15	0	1.27
STR_1	21/05/2008	7.8	262	-1	183.7	60.7	330.4	3.6	600.2	349.8	357	69.6	-1	-1	0.12	0	1.47
STR_2	21/05/2008	7.7	405	-1	392.5	78.3	390.8	9.8	583.3	621.2	607	3.85	-1	-1	0.13	0.05	1.28
Tweeling	21/05/2008	7.8	137	-1	141.1	29.1	131.4	2.7	336.8	107.5	263	1.11	-1	-1	0.15	0.01	1.34
Windpomp 1	21/05/2008	7.8	119	-1	126.1	4.8	131.4	2.2	396.6	111	84	10.44	-1	-1	0.08	0.04	1.19
Sandgat	23/11/2006	7.6	71	-1	52	20	70	1.8	249	29	65	1.4	1	-1	-1	-1	-1
SRK4	23/11/2006	7.5	147	-1	136	37	127	2.5	256	155	289	0.96	0.73	-1	-1	-1	-1
G29947A	05/04/2006	7.6	72	461	79	21	44	1.1	211	17	141	-1	-1	-1	0	0	-1
G29947A	23/11/2006	7.5	62	-1	64	18	38	1	201	14	95	0	0.4	-1	-1	-1	-1
BW Spring	09/08/2007	7.8	80	-1	81	23	60	4.8	355	22	44	0	1	-1	-1	-1	0
BW Manor 2	09/08/2007	7.4	93	-1	71	24	95	4.5	350	39	77	0.67	1.2	-1	-1	-1	0
BW Manor 3	09/08/2007	7.5	95	-1	76	18	103	2.9	345	42	81	0.99	1.3	-1	-1	-1	0
BW Manor 4	09/08/2007	7.5	99	-1	40	1	181	0.78	342	44	84	0.47	1.2	-1	-1	-1	0
S-Dam4	09/08/2007	7.6	31	-1	32	10	14	4.5	127	3.1	18	0.29	0.31	-1	-1	-1	0.1
89701	18/10/1994	7.22	179.3	1179	148.6	41.2	142.9	3.54	249.3	221.8	306.5	2.03	0.87	-1	-1	-1	0.02
89701	10/04/1995	7.72	159.1	1155	154.7	39.3	144.9	3.66	257.2	196.3	294.9	1.427	1.06	-1	-1	-1	0.042
89701	05/12/1995	8.12	217	1309	169.5	35.4	189.3	4.23	241.6	250.1	360	1.117	0.49	-1	-1	-1	0.02
89701	20/05/1996	7.85	159	1066	139.2	34.2	139.7	3.49	236.9	213.7	239.9	1.452	0.94	-1	-1	-1	0.02
89701	13/11/1996	7.9	163.6	1268	169.8	37	166.3	2.96	246.1	231.4	354.4	1.155	0.64	-1	-1	-1	0.02
89701	06/05/1997	7.88	162	1119	150.3	37.5	146.6	2.89	235.5	254.4	234.5	0.911	0.66	-1	-1	-1	0.02
89701	12/11/1997	7.1	156.5	1117	152.8	39.9	135.6	2.55	269.1	185.6	256.2	3.466	0.67	-1	-1	-1	0.02
89701	12/11/1997	7.92	156.5	1121	149.5	46.4	132.1	2.59	267.2	194.4	253.5	3.528	0.71	-1	-1	-1	0.02
89701	21/05/1998	7.2	137.2	1026	140.8	38.4	114	2.52	282.4	158.9	204.4	5	0.67	-1	-1	-1	0.02
89701	23/09/1998	6.9	147.7	1055	136.9	42.5	118.9	2.76	274.9	174.9	220	5.039	0.97	-1	-1	-1	0.046
89701	23/04/1999	7.94	153	1069	148.6	43.9	109.8	2.87	284.8	175.4	217.5	5.185	0.78	-1	-1	-1	0.02
89701	06/05/2000	7.725	175	1216.395	174.482	41.813	135.04	2.941	281.573	219.849	284.334	3.149	0.621	-1	-1	-1	0.02
89701	20/09/2000	8.576	168	1099.203	150.146	38.728	137.25	3.211	263.892	201.608	231.695	3.196	0.579	-1	-1	-1	0.02
89701	25/05/2001	7.997	163	1123.513	156.608	41.44	135.49	2.793	263.127	215.093	237.143	3.03	0.627	-1	-1	-1	0.02
89701	20/09/2001	7.857	169	1058.8	87.784	43.131	141.07	3.246	262.969	207.895	239.988	3.234	0.648	-1	-1	-1	0.02
89701	19/04/2002	7.967	157	1152.573	151.229	46.043	134	3.614	273.348	195.031	271.658	3.828	0.671	-1	-1	-1	0.041

89701	15/09/2002	7.997	171	1174.982	159.92	37.928	144.15	2.55	266.709	226.304	266.701	2.589	0.664	-1	-1	-1	0.041
89701	01/05/2003	7.811	171	1196.166	159.566	38.934	149.99	2.552	248.963	190.215	345.82	1.019	0.944	-1	-1	-1	0.02
89701	26/09/2003	7.656	172	1175.805	174.958	34.46	125.92	2.712	259.234	206.857	307.521	1.472	0.696	-1	-1	-1	0.02
89701	14/05/2004	8.129	182	1267.156	186.799	35.981	170.98	2.854	250.986	228.472	330.173	1.143	0.725	-1	-1	-1	0.015
89701	07/10/2004	7.944	173	1210.104	165.858	30.962	157.03	2.779	261.828	224.739	302.737	1.347	0.745	-1	-1	-1	0.015
89701	02/06/2005	7.824	165	1152.542	159.046	36.389	142.96	2.723	254.173	194.12	300.86	1.164	0.681	-1	-1	-1	0.02
89701	08/09/2005	8.269	167	1106.457	149.155	33.15	143.25	2.743	240.849	193.068	286.411	0.955	0.701	-1	-1	-1	0.042
89701	04/05/2006	7.962	164	1218.337	159.82	35.177	160.63	2.793	250.724	215.854	334.521	0.68	0.747	-1	-1	-1	0.02
89701	13/09/2006	8.078	153	1053.904	137.284	35.204	137.82	2.601	238.34	171.053	274.68	0.864	0.661	-1	-1	-1	0.071
89701	09/05/2007	8.331	190	1196.591	151.63	36.973	159.64	2.599	235.635	231.802	323.33	0.47	0.7	-1	-1	-1	0.116
89701	20/09/2007	8.263	124.9	926	128.11	28.235	120.58	2.659	210.576	144.036	236.025	1.954	0.708	-1	-1	-1	0.144
89939	18/10/1994	7.41	57.4	409	54.8	16.7	25.9	0.53	192.9	11.4	63.2	0.136	0.53	-1	-1	-1	0.02
89939	10/04/1995	8.2	61.7	497	64.7	20.5	30.5	1.62	244	9.2	71.2	0.152	0.69	-1	-1	-1	0.02
89939	05/12/1995	8.35	72	540	81.5	18.4	39.1	2.02	230.1	10.9	106	0.179	0.3	-1	-1	-1	0.02
89939	20/05/1996	7.87	629	513	72.5	18.3	34.8	0.15	231.4	11.8	92.2	0.08	0.46	-1	-1	-1	0.02
89939	13/11/1996	8.01	67.4	550	84.9	16.3	36.4	0.88	238.6	10.7	108.4	0.204	0.33	-1	-1	-1	0.02
89939	06/05/1997	7.61	54.4	417	57.9	18.1	26.9	0.73	195.4	14.8	59	0.112	0.32	-1	-1	-1	0.02
89939	12/11/1997	8.02	58.4	469	63.1	19.9	31.9	0.8	221	15.6	67	0.102	0.31	-1	-1	-1	0.02
89939	21/05/1998	7.61	48.4	407	53.2	17.6	26.9	0.53	205.3	11.1	46.3	0.086	0.3	-1	-1	-1	0.02
89939	23/09/1998	7.8	42.8	348	46.7	16.5	24.8	0.52	166.7	13.3	41.5	0.06	0.51	-1	-1	-1	0.05
89939	23/04/1999	7.76	54.3	451	61.8	19.5	28.6	0.73	226.1	13.6	50.9	0.055	0.33	-1	-1	-1	0.02
89939	08/10/1999	8.011	57.9	456.038	58.455	20.405	29.603	0.707	227.493	12.954	55.39	0.179	0.285	-1	-1	-1	0.02
89939	06/05/2000	7.708	53	402.83	52.008	20.237	27.858	0.644	181.709	26.915	52.487	0.168	0.325	-1	-1	-1	0.02
89939	20/09/2000	7.938	53.8	406.298	52.953	18.735	28.989	0.745	191.739	22.21	48.08	0.066	0.36	-1	-1	-1	0.02
89939	25/05/2001	8.653	57.9	464.277	61.253	22.762	31.668	0.655	219.68	23.432	55.666	0.11	0.313	-1	-1	-1	0.094
89939	20/09/2001	8.357	61.1	459.972	29.531	43.388	28.539	0.784	223.907	20.34	63.43	0.127	0.292	-1	-1	-1	0.042
89939	19/04/2002	7.845	70.1	558.335	74.809	29.128	34.51	0.767	257.117	27.436	77.291	0.11	0.313	-1	-1	-1	0.02
89939	15/09/2002	7.932	66.5	495.363	67.916	23.034	29.25	0.739	215.441	25.373	84.477	0.331	0.302	-1	-1	-1	0.043
89939	30/04/2003	8.041	57.9	435.027	51.917	20.62	28.765	0.538	212.638	18.765	54.371	0.063	0.339	-1	-1	-1	0.082
89939	26/09/2003	7.701	53	401.773	52.637	19.453	26.862	0.723	201.027	16.683	39.511	0.075	0.302	-1	-1	-1	0.02
89939	14/05/2004	7.975	65.3	514.387	67.534	24.848	33.868	0.812	256.631	16.352	57.34	0.055	0.435	-1	-1	-1	0.015
89939	06/10/2004	7.961	76.7	614.452	113.006	8.872	47.361	0.907	226.812	17.018	149.917	0.055	0.497	-1	-1	-1	0.04
89939	01/06/2005	7.933	63.8	540.426	66.438	26.958	34.594	0.826	287.238	16.058	44.727	0.04	0.338	-1	-1	-1	0.02
89939	07/09/2005	7.964	71.9	515.897	77.847	11.21	53.241	0.928	131.682	16.446	194.35	0.04	0.45	-1	-1	-1	0.02
89939	04/05/2006	8.186	88.2	719.838	124.142	13.08	54.024	0.83	235.944	17.222	222.049	0.04	0.489	-1	-1	-1	0.02
89939	12/09/2006	8.322	52.8	387.829	50.249	16.213	26.896	0.522	187.782	13.849	49.995	0.087	0.614	-1	-1	-1	0.051
89939	09/05/2007	8.24	80.2	625.452	104.186	10.586	48.326	0.887	232.016	17.97	159.796	0.04	0.508	-1	-1	-1	0.086
89939	18/09/2007	7.97	96.8	710.276	126.899	9.258	66.475	0.963	212.161	18.333	228.721	0.04	0.581	-1	-1	-1	0.112
91174	07/01/1976	7.86	150	-1	82	44	167	7.95	234.6	206	194	9.29	0.6	-1	-1	-1	-1
91175	28/01/1976	7.73	76	-1	42	8	101	18.9	167.3	57	123	0.75	1.16	-1	-1	-1	-1
91176	03/02/1976	8.09	64	-1	25.5	11.4	88	7.51	176.6	65.8	49.4	1.69	0.39	-1	-1	-1	-1
91177	09/02/1976	7.85	113	-1	30.7	2.3	187.1	12.7	133.5	254.4	34	0.02	1.94	-1	-1	-1	-1
91178	10/02/1976	7.87	86	-1	59	36.2	68.4	3.8	243	93.5	48.4	7.63	0.29	-1	-1	-1	-1
91182	06/04/1976	8.17	65.1	454	55.7	23.6	35.5	2.51	172.7	49.8	39.6	8.24	0.41	-1	-1	-1	0.02
91183	14/05/1976	8.13	89.2	600	56.8	7	108.2	1.48	131.2	36.4	229.2	0.02	0.76	-1	-1	-1	0.02

91184	09/07/1976	7.65	118.6	823	64.5	26.2	138.2	4.05	238.8	114.5	149.1	7.76	0.95	-1	-1	-1	0.02
91185	07/07/1976	7.6	189.2	1236	121.7	23.4	229.3	6.68	153.7	218.4	404.6	9.68	1.86	-1	-1	-1	0.02
91772	03/07/1978	7.9	432.8	2908	183.8	91.6	652.8	35.76	307.7	961.4	586.8	4.3	1.22	-1	-1	-1	0.06
93974	11/01/1985	8.56	46.4	413	39.1	19.2	33.8	3.24	195.9	26	9.8	9.52	0.28	-1	-1	-1	0.04
94748	08/01/1987	8	114	777	77.4	36	109.4	1.62	191.8	126.1	174.7	3.81	0.84	-1	-1	-1	0.04
94748	23/02/1988	8.01	134.1	892	96.2	54.7	99.7	0.86	215.8	172.4	176.6	6.24	0.84	-1	-1	-1	0.02
94748	27/02/1989	6.88	94.6	535	21.8	37.7	98.1	1.88	80.6	166.3	107.9	0.25	0.32	-1	-1	-1	0.9
94748	27/02/1990	7.48	90.3	589	40.4	31.1	98.4	1.62	144.7	151	87.1	0.68	0.25	-1	-1	-1	0.02
94748	14/03/1991	8.09	124	921	104.4	52.6	94.5	0.87	252.9	162.5	172.3	5.452	0.87	-1	-1	-1	0.02
94748	17/03/1992	7.95	115.8	923	104.5	53	88.3	0.78	270.5	154.3	166.3	5.573	0.77	-1	-1	-1	0.082
94749	13/01/1987	7.7	112	711	69.6	32.3	107.9	5.97	127.8	155.2	182.3	0.24	0.43	-1	-1	-1	0.04
94749	24/02/1989	7.64	119.9	842	94.1	34.6	107.7	2.74	211.4	155.1	189.3	0.1	0.45	-1	-1	-1	0.06
94749	27/02/1990	7.69	40.3	323	25.4	8.3	47.1	1.89	158.1	27.8	18.3	0.02	0.7	-1	-1	-1	0.11
94749	15/03/1991	8.16	97.3	780	94.3	32.5	96	2.49	209.7	146.1	152.4	0.041	0.44	-1	-1	-1	0.02
94749	17/03/1992	8.07	123.8	911	113.7	38.5	106.2	2.63	237.1	167.7	192.6	0.02	0.52	-1	-1	-1	0.044
94750	29/01/1987	7.8	130	904	112.7	22.3	133.2	5.21	160.8	118.5	307.4	1.69	1.52	-1	-1	-1	0.04
94750	26/02/1988	8.01	111.4	726	76.8	38.9	87.3	1.73	178.9	124	176.1	0.29	1.29	-1	-1	-1	0.02
94750	26/02/1988	7.97	120.4	775	86	33.8	110.3	2.69	177	148.2	176.7	0.12	0.44	-1	-1	-1	0.02
94750	24/02/1989	7.61	111.3	765	75.6	44.8	89.9	1.96	202.2	133.7	166.7	0.94	1.28	-1	-1	-1	0.02
94750	27/02/1990	7.69	85.5	594	35.6	36.4	91.6	2.91	177.4	117.1	92	0.16	0.45	-1	-1	-1	0.7
94750	15/03/1991	8.22	114.9	773	55.2	12.5	170.7	0.58	132.7	122.3	248.2	0.02	1.67	-1	-1	-1	0.02
94750	17/03/1992	7.94	149	1036	69.9	6.9	249.2	0.85	121.5	119.3	439.6	0.02	1.96	-1	-1	-1	0.02
95329	24/02/1988	7.97	76.2	530	65.6	6.6	82.1	2.03	183.6	35.1	111	0.43	1.33	-1	-1	-1	0.07
95329	27/02/1989	7.55	74.6	535	64.2	5.8	79.3	1.72	194	38.5	106	0.2	1.46	-1	-1	-1	0.02
95329	27/02/1990	7.85	73.6	595	66.3	7	87.5	1.98	206	42.3	135.3	0.67	0.52	-1	-1	-1	0.02
95329	13/03/1991	8.15	105.6	879	140	5	119	0.99	150	41	389	0.02	1.42	-1	-1	-1	0.02
95329	18/03/1992	8.48	119.8	946	155.5	3.1	114.7	0.91	169.6	59.1	404	0.02	1.23	-1	-1	-1	0.02
95330	24/02/1988	8.2	135.2	941	136.2	36.7	95.9	3	221.5	148.8	223.5	5.72	0.97	-1	-1	-1	0.05
95330	27/02/1989	6.76	453	3968	559.3	65.4	556	6.3	86.1	325.3	2340.9	1.68	1.84	-1	-1	-1	0.07
95330	27/02/1990	7.77	165	1162	135.8	26.2	190.7	3.69	200	160.5	361.3	8.75	1.43	-1	-1	-1	0.02
95330	13/03/1991	7.88	533	4587	538.6	16.5	911	4.05	33.1	459	2613.4	0.09	3.36	-1	-1	-1	0.067
95331	24/02/1988	8.11	148.8	1002	110	59.8	119.7	0.78	216.2	201.7	231.8	3.18	0.49	-1	-1	-1	0.02
95331	27/02/1989	7.08	50.1	320	27	11.7	53.9	1.34	106.4	90.3	2	0.36	0.39	-1	-1	-1	0.39
95331	26/02/1990	7.81	56.6	327	28.3	14.3	54.6	0.84	65	122.1	26	0.08	1.32	-1	-1	-1	0.16
95331	13/03/1991	8.15	77	558	66.3	15.8	74.3	0.87	182.4	86.5	89.9	0.319	0.49	-1	-1	-1	0.056
95331	16/03/1992	8.51	72.3	498	61	11.9	66.3	0.75	176.3	67.3	75.5	0.02	0.46	-1	-1	-1	0.02
95332	25/02/1988	7.97	158.1	999	113.5	48.1	144	1.6	190.8	259.5	189.2	2.14	0.67	-1	-1	-1	0.04
95332	23/02/1989	7.64	227.3	1366	162.8	69.7	173.5	1.94	222.8	406.8	261	4.08	0.55	-1	-1	-1	0.02
95332	26/02/1990	7.63	202	1326	136.3	69.9	178.2	2.79	210.9	396.6	272.5	2.71	0.22	-1	-1	-1	0.27
95332	15/03/1991	7.99	175	1319	158.5	70.9	173.9	2.21	207.8	420.5	222.1	3.74	0.77	-1	-1	-1	0.02
95332	16/03/1992	8.12	219	1353	172.7	70.3	167.9	2.22	239.6	386.7	242.5	3.988	0.56	-1	-1	-1	0.059
95332	09/11/2005	7.762	240	1432.845	172.322	85.041	175.63	2.665	185.735	482.469	260.923	6.053	0.43	-1	-1	-1	0.02
95332	17/10/2007	7.702	212	1368.984	173.74	65.118	164.58	2.006	258.01	395.916	235.709	3.758	0.455	-1	-1	-1	0.121
95333	25/02/1988	8.11	150.6	1021	123.9	44.6	130	2.42	246.3	202	209.5	1.62	0.62	-1	-1	-1	0.73
95333	23/02/1989	7.61	136	973	106.5	41.1	131.1	2.62	263.2	185.8	184.4	0.09	0.59	-1	-1	-1	0.02

95333	26/02/1990	8.15	98.4	635	19.8	38.8	127.4	2.68	148.5	199.8	64.3	0.05	0.81	-1	-1	-1	0.05
95333	15/03/1991	8.04	117.6	934	95.9	41	127.8	2.11	225.8	205.3	173.6	2.696	0.65	-1	-1	-1	0.02
95333	16/03/1992	8.2	126.8	885	86.2	40.4	122.3	2.08	240.4	177.1	160.8	0.45	0.48	-1	-1	-1	0.058
149652	24/05/1976	7.83	72.9	528	51.9	18.6	76.7	3.43	174.2	46.6	113.4	0.97	0.42	-1	-1	-1	0.25
149829	16/06/1976	6.76	149.2	1036	133.2	52.4	97.2	6.54	236.4	125.3	259.9	16.4	0.62	-1	-1	-1	0.06
149830	16/06/1976	7.79	193.2	1307	162.1	45.1	161.4	27.31	184.7	216.9	439.1	6.4	0.66	-1	-1	-1	0.73
152898	04/03/1976	7.91	407.5	2621	266.9	200.8	302.1	23.37	267.6	802.1	636.3	14.14	0.67	-1	-1	-1	0.14
155589	14/03/1977	7.78	130	923	116.8	22.5	133.5	0.95	234	129.9	232.3	0.09	0.78	-1	-1	-1	0.02
155589	23/03/1977	7.99	111	800	103.8	23.1	97.1	0.64	242.7	95.3	169.4	3.23	0.6	-1	-1	-1	0.02
156565	20/09/1977	7.63	117.1	708	73.9	12	118	0.15	166.8	95.8	203.4	0.08	0.62	-1	-1	-1	0.02
156565	07/11/2005	7.881	77.8	650.997	74.089	18.298	81.27	4.307	307.83	46.734	48.403	0.379	0.651	-1	-1	-1	0.02
156565	08/05/2006	8.21	72.6	571.004	48.601	20.618	79.009	4.084	258.939	46.256	55.773	0.04	0.594	-1	-1	-1	0.084
156565	15/10/2007	8.335	96.5	591.337	28.342	17.499	93.977	5.155	289	54.898	37.826	0.04	0.691	-1	-1	-1	0.092
156578	21/09/1977	7.48	76.2	565	67.8	17.1	64	2.51	250.4	50.7	46.6	2.29	0.69	-1	-1	-1	0.02
156578	07/11/2005	7.847	77.4	646.099	81.579	18.752	62.798	3.056	322.065	35.845	41.765	2.006	0.66	-1	-1	-1	0.02
156578	06/11/2006	8.267	55.7	417.131	26.705	15.251	69.787	3.005	154.059	35.948	72.123	1.304	0.549	-1	-1	-1	0.076
156578	15/10/2007	7.622	76.6	639.046	86.187	17.545	59.514	2.331	317.421	34.825	48.243	0.558	0.653	-1	-1	-1	0.076
164085	12/04/1984	7.9	131	974	136.9	22.8	126.6	1.05	246.9	113.8	269.9	0.17	0.58	-1	-1	-1	0.05
164085	30/04/1984	7.71	126.7	943	121.8	19.1	133.8	0.96	226.6	110.2	277.8	0.44	0.63	-1	-1	-1	0.02
164085	07/11/2005	7.801	67.7	485.093	55.213	16.399	52.147	2.765	232.963	35.847	37.891	0.04	0.538	-1	-1	-1	0.02
164892	17/12/1984	7.6	125.4	733	87	58.9	68.8	2.26	119.4	211.1	124.4	7.87	0.05	-1	-1	-1	0.4
166259	02/02/1987	7.5	129	785	51.1	15.6	169.4	30.37	105.6	209	176.4	0.57	2.2	-1	-1	-1	0.04
166259	24/02/1988	8.06	197	1158	140	78.1	116.5	1.91	250.3	282.7	214.5	4.21	0.56	-1	-1	-1	0.04
166259	27/02/1990	7.9	195	1230	161	85.8	117.4	2.56	202	343.7	257.5	3.22	0.89	-1	-1	-1	0.04
166259	13/03/1991	8.22	188	1320	171.1	84	117.2	2.31	293.4	335	239.4	2.818	0.55	-1	-1	-1	0.02
166259	18/03/1992	8.24	183	1220	157.2	62.1	122	1.55	282.2	290.8	239.9	0.444	0.63	-1	-1	-1	0.059
166613	01/03/1988	7.78	174	1153	121.6	7.9	242.9	1.66	145.8	222.4	375.1	0.44	1.67	-1	-1	-1	0.02
166613	23/02/1989	7.43	193.1	1178	121.5	7.8	236.7	1.25	167	224.8	378.4	0.44	1.78	-1	-1	-1	0.02
166613	26/02/1990	7.88	173	1186	111.4	9.6	255.7	1.62	156	234.8	380.7	0.39	0.54	-1	-1	-1	0.02
166613	15/03/1991	8.16	141	1140	116.7	7.2	242.7	1.23	156.7	228.1	347.5	0.674	1.99	-1	-1	-1	0.02
166613	19/03/1992	8.06	251	1758	189.9	95.2	260.1	1.2	224.5	579	351.4	1.46	0.46	-1	-1	-1	0.059
166614	24/02/1988	8.34	210.6	1347	185.1	70.9	136.7	1.76	283.4	255.9	328.9	4.81	0.69	-1	-1	-1	0.02
166614	27/02/1989	7.96	204.5	1392	182.1	72.3	132.3	1.79	321.6	245.3	342.9	5.18	0.59	-1	-1	-1	0.07
166614	27/02/1990	7.81	177	1335	165.6	68.6	127.9	2.02	344.7	220.8	299.6	6.42	1.27	-1	-1	-1	0.04
166614	16/03/1992	8.34	182	1284	160.3	68	127.3	1.48	338.9	215.7	276	4.912	0.6	-1	-1	-1	0.062
166615	25/02/1988	8.06	153.6	987	118.1	43.1	134.2	1.08	188.8	242.1	212.9	1.05	0.41	-1	-1	-1	0.04
166615	23/02/1989	6.61	112.8	620	23.7	36.4	139.9	1.84	52.1	244.4	109.1	0.24	0.22	-1	-1	-1	0.16
166615	26/02/1990	7.33	98.8	536	24.3	21.6	133.4	1.71	17.6	256.1	76.8	0.08	0.11	-1	-1	-1	0.02
166615	15/03/1991	8.18	78	459	19.6	14.7	129.9	1.31	18.8	256.9	12.2	0.183	0.31	-1	-1	-1	0.044
166615	16/03/1992	8.1	115.7	628	37.2	31.6	129.4	1.26	45.3	255.6	116.7	0.053	0.31	-1	-1	-1	0.397
166616	25/02/1988	4.45	135.4	637	80.8	27.4	112.6	2.66	5.4	400.9	4	0.09	0.15	-1	-1	-1	1.29
166616	23/02/1989	7.43	357.1	2201	133.3	101.5	475.4	2.67	191.6	760	483.5	1.76	0.53	-1	-1	-1	2.22
166616	26/02/1990	7.22	150	769	80.7	39	126.2	3.58	46.1	439.9	20	0.02	0.6	-1	-1	-1	1.89
166616	16/03/1992	8.04	230	1350	215	61.9	148.8	0.95	170.7	463.9	250.8	0.02	0.24	-1	-1	-1	0.058
166617	25/02/1988	8.43	213.3	1397	181.5	84.6	136.6	0.62	327.3	243.2	340.6	2.22	0.46	-1	-1	-1	0.04

166617	23/02/1989	7.76	205.9	1390	162.8	82.7	132.9	0.77	320.5	239.3	370.6	2.25	0.45	-1	-1	-1	0.08
166617	26/02/1990	7.93	156	1121	104.6	63.5	134.2	0.98	289.5	184.6	265.8	3.1	0.36	-1	-1	-1	0.06
166617	12/03/1991	7.73	141	1145	111.8	68.3	135.7	0.72	305.3	185.8	257.3	2.882	0.67	-1	-1	-1	0.02
166617	16/03/1992	8.31	175	1284	155.3	70	132.6	0.64	375.1	184.8	268	3.299	0.52	-1	-1	-1	0.058
166617	07/11/2005	7.614	118.6	867.066	72.039	49.095	113.08	0.817	266.811	124.681	172.788	1.989	0.362	-1	-1	-1	0.02
166618	26/02/1988	8.06	134.2	881	106	16.9	149.9	1.53	185.5	166.1	213.7	0.06	0.57	-1	-1	-1	0.02
166618	24/02/1989	7.67	131.5	936	114.1	20.5	146.2	1.56	205.6	167.5	233.5	0.23	0.52	-1	-1	-1	0.02
166618	27/02/1990	7.87	128.4	942	115.3	28	124.9	2.14	241.2	176.4	200.7	0.12	0.34	-1	-1	-1	0.04
166618	15/03/1991	8.27	128.4	938	119.2	21.7	144.4	1.34	203.8	189.8	211.5	0.147	0.56	-1	-1	-1	0.02
166618	17/03/1992	8.18	125.6	918	120.4	22.7	127.7	1.33	223.2	175.5	197.9	0.02	0.46	-1	-1	-1	0.062
166619	26/02/1988	7.78	94.7	554	13.5	37	111.1	3.97	163.3	168.4	14.8	1.26	0.25	-1	-1	-1	0.49
166619	27/02/1989	7.58	98	625	19.6	40.5	112.4	8.28	202.6	176.5	2	4.06	0.27	-1	-1	-1	0.05
166619	27/02/1990	7.56	96.1	661	21.5	41.5	112.4	8.46	210.6	179.2	5.4	7.71	1.32	-1	-1	-1	0.04
166619	15/03/1991	8.15	121.1	856	83.2	45.3	110.3	2.44	223.2	184.5	138.5	4.249	0.48	-1	-1	-1	0.02
166619	17/03/1992	8.08	141	990	98.1	56.1	120.9	0.6	246.5	204.1	194.5	3.181	0.58	-1	-1	-1	0.04
166619	19/03/1992	8.24	161	1166	125.4	5.9	244.8	1.11	162.2	225.8	361.5	0.351	1.81	-1	-1	-1	0.044
166620	26/02/1988	7.69	113.3	644	62.6	34.8	101.9	2.47	124	212.3	74.2	0.92	0.42	-1	-1	-1	0.02
166620	27/02/1989	7.79	135.1	931	112.8	45.1	103	2.28	222.1	198.2	179.5	4.21	0.61	-1	-1	-1	0.04
166620	27/02/1990	7.93	144	1020	134.8	48.7	104.8	2.81	253.8	189.8	198	6.9	0.56	-1	-1	-1	0.02
166620	13/03/1991	8.27	136	946	117.3	47.7	96.6	1.88	249.8	174.8	178.8	5.405	0.66	-1	-1	-1	0.02
166620	17/03/1992	8.27	123.6	998	131.1	43.6	101.6	2.23	273.8	168.6	191.6	5.604	0.77	-1	-1	-1	0.059
166621	26/02/1988	8.01	101.1	683	90.3	7.4	108.8	1.16	197.4	100.7	125.4	1.82	0.49	-1	-1	-1	0.04
166621	27/02/1989	7.79	124.5	888	115	31.1	106.1	1.52	238.9	151.9	172.3	4.21	0.56	-1	-1	-1	0.02
166621	27/02/1990	8.14	118.8	917	115.7	32.8	107.8	1.83	260	150.3	170.3	4.59	0.53	-1	-1	-1	0.02
166621	13/03/1991	8.19	99.2	713	95.4	9.5	106.2	1.17	209.5	107.5	128.4	1.983	0.56	-1	-1	-1	0.02
166621	17/03/1992	8.08	112.1	783	110.5	9.8	108.7	1.33	205.2	140.9	151.7	2.126	0.48	-1	-1	-1	0.052
166622	26/02/1988	8.11	156.6	1067	138.3	54	116	0.93	248	201.4	222.6	6.88	0.62	-1	-1	-1	0.02
166622	27/02/1989	7.87	153.8	1123	142	59.5	107.7	1.2	287.7	215.1	214.8	7.15	0.57	-1	-1	-1	0.06
166622	27/02/1990	8.06	159	1187	144.9	67.2	112.1	1.57	317.2	219.1	224.6	6.7	0.39	-1	-1	-1	0.02
166622	13/03/1991	8.09	291	2238	244	28.1	399.6	2.38	157.7	248.5	1109.4	2.732	1.94	-1	-1	-1	0.02
166622	17/03/1992	8.31	173	1165	142.3	64.4	111.9	1.01	308.7	215.7	226	5.934	0.45	-1	-1	-1	0.055
166623	29/02/1988	7.74	160.1	1073	132.3	13.8	192.1	1.56	142.1	190.7	366.8	0.46	0.77	-1	-1	-1	0.02
166623	24/02/1989	7.67	132.8	1002	125.5	21.2	139.8	3.81	227.3	96.2	331	1.36	0.77	-1	-1	-1	0.04
166623	27/02/1990	7.8	114.4	848	63	14.5	168.4	2.25	210	120.1	219.9	0.55	0.55	-1	-1	-1	0.06
166623	14/03/1991	8.28	115.9	833	71.8	10.7	170.7	1.36	182.9	116.2	237.5	0.104	0.89	-1	-1	-1	0.02
166623	18/03/1992	7.85	514	4751	559.9	14.3	945	3.27	67.9	427.8	2713.8	0.094	3.48	-1	-1	-1	0.058
166624	29/02/1988	8.01	284.2	1525	194.1	86.1	206.7	12.44	148.5	701.6	121.2	4.85	0.51	-1	-1	-1	0.04
166624	24/02/1989	7.52	241.1	1312	77.3	56.1	286.4	6.33	183.8	581.9	72.1	1.51	0.57	-1	-1	-1	0.08
166624	26/02/1990	7.95	224	1258	85.2	62.4	270.8	6.44	154.7	564.6	78.4	0.07	1.61	-1	-1	-1	0.04
166624	14/03/1991	8.34	258	1502	173.2	81.3	203.9	11.75	166.9	680.6	118.1	6.477	0.55	-1	-1	-1	0.02
166624	19/03/1992	8.3	240	1508	175.7	82	205	12.12	186.9	669.3	110.5	5.54	0.66	-1	-1	-1	0.066
166625	29/02/1988	8.29	943.4	6193	174.3	336	1520.3	0.15	332.7	1753	1990.9	2.63	1.39	-1	-1	-1	0.02
166625	23/02/1989	7.9	618.3	3756	136.1	174	889.9	1.93	287.7	1184.9	999.5	3.79	1	-1	-1	-1	1.13
166625	26/02/1990	8.13	747	5545	119.3	276.4	1423.6	4.76	348	1530.8	1751.3	3.05	0.55	-1	-1	-1	0.02
166625	14/03/1991	8.34	633	-1	162.5	258.9	1324.7	3.75	596	1513.6	1551.2	2.272	1.75	-1	-1	-1	0.02

166625	19/03/1992	8.5	732	5778	127.2	249.6	1427.2	3.33	667.7	1532.3	1607.8	3.333	1.49	-1	-1	-1	0.078
166627	04/03/1988	8.11	85.8	578	50.9	23	81.4	7.47	235.5	59.8	44.2	5.32	0.57	-1	-1	-1	0.05
166627	24/02/1989	7.84	83.3	613	55.1	24	79.3	7.57	259.4	61.4	45.6	5.2	0.56	-1	-1	-1	0.02
166627	27/02/1990	7.84	78.1	639	48.8	24.3	84.6	8.01	275	60.9	49.8	5.58	1.34	-1	-1	-1	0.43
166627	14/03/1991	8.1	76.4	592	51.6	22.8	79.3	7.68	256.4	56.6	38.6	5.098	0.54	-1	-1	-1	0.02
166627	18/03/1992	8.29	110.4	856	75.3	9.6	175.2	1.14	182.5	116.4	254	0.02	1.23	-1	-1	-1	0.02
169759	09/06/1992	8.1	146	889	70.4	45.7	144.1	2.56	193.6	255	125.7	1.976	0.52	-1	-1	-1	0.02
170306	01/02/1993	1	3840	5497	132.6	42.1	142.1	9.58	2	4503.3	666.3	0.04	0.84	-1	-1	-1	0.118
170306	07/11/2005	7.429	123.3	889.494	101.2	41.96	103.93	2.632	219.182	155.555	197.164	4.328	0.562	-1	-1	-1	0.02
170306	15/10/2007	7.603	65.2	416.612	46.603	9.357	72.014	1.055	70.538	72.062	127.192	0.221	1.172	-1	-1	-1	0.081
200000227	26/06/2001	8.544	123.7	952.388	19.815	36.922	199.4	2.844	353.153	77.01	178.511	1.145	2.086	-1	-1	-1	0.058
1000005307	08/09/2003	7.604	199	1356.113	104.175	48.457	237.87	3.795	407.1	262.524	192.452	2.179	0.762	-1	-1	-1	0.02
1000005309	08/09/2003	7.701	31.1	213.976	24.314	7.619	20.407	1.356	98.866	17.044	13.056	2.072	0.322	-1	-1	-1	0.02
1000005311	08/09/2003	7.613	128.2	938.122	107.743	28.216	135.99	1.492	318.44	176.827	96.875	0.434	0.705	-1	-1	-1	0.02
1000005313	08/09/2003	7.773	107.6	760.63	87.085	14.202	113.13	2.922	288.02	86.837	93.493	2.444	0.9	-1	-1	-1	0.02
1000005315	09/09/2003	7.682	73	543.246	66.257	15.85	60.612	1.628	236.43	49.438	54.487	1.367	0.533	-1	-1	-1	0.044
1000005317	09/09/2003	7.788	91.1	682.032	62.069	5.845	123.7	2.282	266.592	63.247	97.997	0.113	1.207	-1	-1	-1	0.072
1000005319	09/09/2003	7.441	157	1000.952	146.68	16.624	145.7	1.77	241.32	241.74	117.353	8.197	0.486	-1	-1	-1	0.02
1000005321	09/09/2003	7.835	98.3	743.234	91.252	17.321	104.68	2.028	282.88	100.791	75.456	1.332	0.81	-1	-1	-1	0.02
1000005323	09/09/2003	7.609	93	677.53	76.853	18.133	89.981	1.185	254.039	104.806	69.38	1.515	0.663	-1	-1	-1	0.02
1000005325	09/09/2003	7.928	88.7	680.086	80.655	15.543	82.334	1.783	291.573	66.538	72.227	1.065	0.699	-1	-1	-1	0.02
1000005327	09/09/2003	7.522	82.3	648.461	77.745	13.778	87.125	3.11	286.826	49.618	59.32	1.634	0.718	-1	-1	-1	0.02
1000011055	08/11/2005	7.779	20.7	139.22	15.909	5.309	11.954	0.533	68.53	7.031	9.729	1.113	0.188	-1	-1	-1	0.02
1000011055	07/11/2006	7.866	24.9	196.28	25.269	7.889	19.154	0.563	93.434	6.996	21.939	0.04	0.166	-1	-1	-1	0.106
1000011055	15/10/2007	7.423	102	754.136	71.908	28.366	113.8	0.578	244.4	94.639	145.648	0.105	0.599	-1	-1	-1	0.078
1000011055	16/10/2007	7.209	26.7	189.963	24.702	8.063	14.063	0.362	96.599	7.186	16.987	0.108	0.222	-1	-1	-1	0.058
1000259865	07/11/2006	7.921	93.2	684.895	54.701	20.36	120.73	2.281	239.451	85.497	107.587	0.213	0.678	-1	-1	-1	0.077

13. APPENDIX B: STABLE ISOTOPE DATA

Table 11: Listing of stable isotope data.

Source#	Borehole ID	DWA #	X-Coord	Y-Coord	field EC (mS/m)	Date	δD‰	δ18O‰	Source
1	Bulkraal	G29947A				2006/04/05	-27.6	-4.7	GEOSS sampling
2	Waterval (Bh HB 21/45)					2006/04/05	-27.2	-4.5	GEOSS sampling
3	Waterval (Fontein)						-27.2	-4.6	GEOSS sampling
4	Brandwag 09	G29858V				2006/04/05	-33.4	-5.1	GEOSS sampling
5	Brandwag 02	G29894L				2006/04/05	-34.5	-5.9	GEOSS sampling
6	Brandwag 12					2006/04/05	-31.4	-5.2	GEOSS sampling
7	SRK3					2006/04/05	-34.2	-5.7	GEOSS sampling
8	LN	G29879BC				2006/04/05	-28.4	-4.9	GEOSS sampling
9	Noordeinde_Suid/HB921_43					2006/04/05	-3.7	-0.7	GEOSS sampling
10	Volstruisgat	G29946D				2006/04/05	-30.5	-4.9	GEOSS sampling
11	Brandwag 08	G29858B				2006/04/05	-35.6	-5.9	GEOSS sampling
12	Noordeinde_Noord/HB21_41					2006/11/23	-12.3	-2.17	GEOSS sampling
13	Town spring					2006/04/05	1.4	0.07	GEOSS sampling
14	BW_Manor2					2007/08/09	-2.9	-0.75	GEOSS sampling
15	BW_Manor3					2007/08/09	-5.1	-1.09	GEOSS sampling
16	BW_Manor4					2007/08/09	-7	-1.37	GEOSS sampling
17	S-Dam_4					2007/08/09	-12.3	-2.29	GEOSS sampling
BW1a	Speelmanskuil	G29877P	32.26216	22.79802		1978/08/16		-5.7	Vogel et al 1980
BW2a	Speelmanskuil	G29878A	32.30410	22.73691		1978/08/17		-5.9	Vogel et al 1981
BW3a	Lower Plaatdoorns	G29943G	32.41910	22.78857		1978/08/17		-4.8	Vogel et al 1982
BW4a	Brandwag	G29858S	32.21066	22.81915		1978/08/18		-5.1	Vogel et al 1983
BW5a	Slagterskop	G29869H	32.21783	22.73235		1978/08/19		-5.6	Vogel et al 1984
BW5c	Slagterskop	G29869H	32.21783	22.73235		1978/08/19		-5.6	Vogel et al 1985
BW6		G29940BB	32.22192	22.70883		1978/08/19			Vogel et al 1986
BW7	Bulskop	G29935C	32.38772	22.67367		1978/08/21		-5.4	Vogel et al 1987
BW8	S Lemoenfontein	G29879BQ	32.28355	22.61613		1978/08/21		-5.4	Vogel et al 1988
BW9	De Hoop		32.09000	22.73833		1978/08/22		-5.4	Vogel et al 1989
BW10	De Hoop	G29863D	32.10407	22.74849		1978/08/22		-6	Vogel et al 1990
BW11	De Hoop	G29893	32.12967	22.69941		1978/08/22		-5.5	Vogel et al 1991
BW12	De Hoop		32.13778	22.67667		1978/08/22		-5.6	Vogel et al 1992
BW13	Rhenosterkop	G29902FB	32.21972	22.86246		1978/08/23		-4.5	Vogel et al 1993
BW14	De Hoop		32.07500	22.72667		1978/08/23		-6	Vogel et al 1994
BW15	De Hoop	G29870N	32.16300	22.74496		1978/08/24			Vogel et al 1995

14. APPENDIX C: RADIOCHEMISTRY DATA

Table 12: Radiochemistry laboratory results (NECSA) 2008 and 2009.

mBq/L	**Blydskap 01**			**Blydskap 02**			**Schr Fontein 2**			**Steenrotsfontein**			**Spring**		
Nuclide	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA
^{238}U	123	8	4.9	158	10	4.2	132	8	1.3	641	26	7.6	184	13	6.6
^{234}U	554	16	3.3	584	18	4.2	380	13	1.3	1380	40	9.5	465	21	2.4
230Th	7.9	8.1	15	6.3	6.6	14	6.8	7	14	15.1	3.4	7.8	7.9	8.6	20
^{226}Ra	9.49	2.1	4.9	16.4	2.4	0.93	6.07	1.53	3	12.9	2.1	3.2	1.6	1	3.3
^{210}Pb	39.9	10.1	4.8	40.5	10.3	5.1	26.2	7	3.9	25	9.6	7.7	35.7	11.1	7.3
^{210}Po	-3.4	4.5	1.3	-3.2	4.5	0.85	-6.7	2.4	1.3	-4.1	5.2	1.1	-7.8	6	0.85
^{235}U	5.68	0.35	0.22	7.3	0.44	0.2	6.51	1.86	3.4	29.5	1.2	0.35	8.49	0.59	0.3
227Th	2	1.3	4.1	2.4	1.2	2.7	2.5	1.1	2.8	6.79	2.26	4.3	7.3	3.2	8.4
^{223}Ra	-1	1.6	5.5	-1.5	1.4	1.2	0.47	1.3	3.8	10.9	2.9	5	4.85	1.77	4.6
^{232}Th	1.3	0.75	1.2	0.81	0.57	1.1	1.27	0.73	1.1	2.3	1	2.6	2.83	1.64	2.6
228Th	1.8	1	2.8	2.2	1.1	3.3	0.42	0.42	1.1	13.9	2.3	0.99	3.9	2.6	8.4
^{224}Ra	3.18	1.42	1.7	1.5	1	2	0.68	1.2	5	6.94	2.38	4.9	1.6	1.1	2.2
	Tulplaagte 357			**Katdoornkuil**			**Aarddorings**			**Hansrivier 13**			**Olivegrove 3**		
Nuclide	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA
^{238}U	244	11	3.4	325	12	4.4	95.4	6	2.7	175	8	1.1	164	9	3.3
^{234}U	738	19	3.4	1100	20	3.5	192	9	1	465	14	3.6	282	12	4.8
230Th	12	3.1	17	16.3	3.7	16	12	2.9	16	8.2	8.4	14	22	4.8	16
^{235}U	11.2	0.5	0.16	15	0.6	0.2	4.54	1.51	3.5	8.05	0.38	0.049	7.55	0.4	0.15
227Th	1.3	1.8	5.6	1.6	1.6	3.3	3.98	1.58	1.2	2.7	1.6	4.4	2.9	1.9	3.3
^{232}Th	8.8	2.12	3.4	15.7	2.7	1.2	5.34	1.54	1.2	9.3	1.94	1.1	5	1.51	1.2
228Th	5	2.1	6	10.2	2.3	4.1	4.4	1.8	4.7	3.2	1.6	4.8	10.3	2.7	6.3
Gross alpha	472	147	460	490	160	500	-110	130	440	160	160	540	180	130	430
Gross beta	-150	340	1100	-22	340	1100	-440	330	1100	-120	340	1100	-110	330	1100
	Hoenderhok			**Saucyskuil**			**Steenrotsfontein 1**			**Hansrivier 10**			**Hansrivier 12**		
Nuclide	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA
^{238}U	325	22	4	54.2	4.7	1.1	274	10	2.8	188	15	3.3	30.9	6.9	10
^{234}U	536	29	16	261	10	4.3	565	15	3.6	455	24	13	71.5	10.7	15
230Th	6.7	6.9	15	19.1	4.3	18	37.5	7.3	21	17	3.9	17	19.6	4.1	15
^{235}U	15	1	0.19	2.5	0.22	0.051	12.6	0.5	0.13	8.66	0.7	0.15	1.42	0.32	0.48
227Th	4.13	1.81	3.8	6.73	2.79	4.6	2.6	1.83	1.6	4.7	2	5.1	0.89	1.2	3
^{232}Th	33.1	3.7	3	2	1.2	3.7	4.71	1.67	1.6	7.13	1.84	1.3	1.2	0.92	3
228Th	6.94	1.68	1.1	8.25	2.22	4.5	9.3	2.33	1.6	1.4	1.6	5.6	4.1	1.7	4.9
Gross alpha	84	160	540	87	130	420	637	179	560	130	150	500	-210	140	480
Gross beta	-51	340	1100	-10	330	1100	41	340	1100	-92	340	1100	-200	340	1100

Table 13: Listing of radiochemistry data.

#		Year	X-coord	Y-coord	Elevation	Field	EC	Gross alpha	Gross beta	238U	234U	234U/238U	230Th	226Ra	210Pb	210Po	235U	227Th	223Ra	232Th	228Th
					(masl)	pH	mS/m	Act.	Act.	Act.	Act.	ratio	Act.	Act.	Act.	Act.	Act.	Act.	Act.	Act.	Act.
26	Town Spring	2008	22.58524	32.34573	851	6.92	62			184	465	2.53	< 20	< 3.3	35.7	< 0.85	8.49	< 8.4	4.85	2.83	< 8.4
27	Steenrotsfontein 01	2008	22.56430	32.41827	808	7.13	250			641	1380	2.15	15.1	12.9	25	< 1.1	29.5	6.79	10.9	< 2.6	13.9
29	Blydskap 01	2008	23.13905	32.61653	842	7.07	104			123	554	4.50	< 15	9.49	39.9	< 1.3	5.68	< 4.1	< 5.5	1.3	< 2.8
30	Blydskap 02	2008	23.09525	32.60788	831	7.11	87			158	584	3.70	< 14	16.4	40.5	< 0.85	7.3	< 2.7	< 1.2	< 1.1	< 3.3
33	Scheurfontein 02	2008	22.57533	32.68559	871	7.01	76			132	380	2.88	< 14	6.07	26.2	< 1.3	6.51	< 2.8	< 3.8	1.27	< 1.1
34	Steenrotsfontein 07	2009	22.53447	32.39173	815	6.64	160	637	< 1 100	274	565	2.06	37.5				12.6	2.6		4.71	9.3
35	Aarddorings	2009	22.56148	32.64715	838	7.00	73	< 440	< 1 100	95.4	192	2.01	< 16				4.54	3.98		5.34	< 4.7
36	Tulplaagte 357	2009	22.65663	32.65033	874	7.41	125	472	< 1 100	244	738	3.02	< 17				11.2	< 5.6		8.8	< 6.0
37	Katdoornkuil	2009	22.75134	32.70107	866	7.06	169	< 500	< 1 100	325	1100	3.38	16.3				15	< 3.3		15.7	10.2
38	Hansrivier 10	2009	22.64032	32.39104	844	6.99	148	< 500	< 1 100	188	455	2.42	< 17				8.66	< 5.1		7.13	< 5.6
39	Hansrivier 12	2009	22.60189	32.39853	833	7.01	110	< 480	< 1 100	30.9	71.5	2.31	19.6				1.42	< 3.0		< 3.0	< 4.9
40	Hansrivier 13	2009	22.64117	32.38757	845	6.99	160	< 540	< 1 100	175	465	2.66	< 14				8.05	< 4.4		9.3	< 4.8
41	Hoenderhok	2009	22.59773	32.36280	841	7.00	184	< 540	< 1 100	325	536	1.65	< 15				15	4.13		33.1	6.94
42	Saucyskuil	2009	22.79733	32.53846	847	7.96	73	< 420	< 1 100	54.2	261	4.82	19.1				2.5	6.73		< 3.7	8.25
43	Olivegrove 3	2009	22.58652	32.50932	838	7.44	62	< 430	< 1 100	164	282	1.72	22				7.55	< 3.3		5	10.3
										CSIR ANALYTICAL DATA											
BW1a	Speelmanskuil	1978	22.79802	32.26216		7.43	151							24.3							
BW2a	Speelmanskuil	1978	22.73691	32.30410		7.86	165			36	159	4.40		71.8							
BW3a	Lower Plaatdoorns	1978	22.78857	32.41910		7.13	245			273	1016	3.72		8.6							
BW4a	Brandwag	1978	22.81915	32.21066		7.14	128							20.7							
BW5a	Slagterskop	1978	22.73235	32.21783		7.39	114			19.4	87	4.48		9.8							
BW5c	Slagterskop	1978	22.73235	32.21783		7.38	113			15.7	66	4.17		13.1							
BW7	Bulskop	1978	22.67367	32.38772		7.03	974			559	1827	3.27		10.5							
BW8	S Lemoenfontein	1978	22.61613	32.28355		7.19	141			251	598	2.38		39.8							
BW9	De Hoop	1978	22.73833	32.09000		6.97	70							15.2							
BW10	De Hoop	1978	22.74849	32.10407		7.00	91			108	264	2.44		23.1							
BW11	De Hoop	1978	22.69941	32.12967		7.16	74							7.9							
BW12	De Hoop	1978	22.67667	32.13778		7.06	106			62	144	2.31		12.4							
BW13	Rhenosterkop	1978	22.86246	32.21972		7.05	158			174	781	4.49		9.2							
BW14	De Hoop	1978	22.72667	32.07500		7.41	54							9.5							

Table 14: Total radioactive dose results of Beaufort West samples compared to the South African water quality guidelines (DWAF, 2002).

		LIFETIME DOSE CALCULATION							Total Radioactive Dose	
Sample	Age range	< 1 a	1-2 a	2-7 a	7-12 a	12-17 a	> 17 a	Average life-time	Chemical	
#	Consumption (L/a)	200	260	300	350	600	730	exposure	toxicity	
	Dose rate (mSv/a)							mSv/a	mBq/L	mg/L
26	Town Spring	####	0.055	0.044	0.047	0.085	0.049	**0.053**	184	**0.015**
27	Steenrotsfontein 01	####	0.116	0.090	0.091	0.159	0.111	**0.115**	641	**0.052**
29	Blydskap 01	####	0.063	0.048	0.050	0.091	0.050	**0.055**	123	**0.010**
30	Blydskap 02	####	0.067	0.051	0.054	0.100	0.055	**0.060**	158	**0.013**
33	Schr Fontein 02	####	0.036	0.030	0.033	0.062	0.034	**0.037**	132	**0.011**
34	Steenrotsfontein 07	####	0.034	0.026	0.026	0.043	0.037	**0.045**	274	**0.022**
35	Aardorings	####	0.012	0.009	0.009	0.015	0.013	**0.016**	95	**0.008**
36	Tulplaagte 357	####	0.036	0.028	0.027	0.046	0.038	**0.045**	244	**0.020**
37	Katdoornkuil	####	0.052	0.041	0.040	0.068	0.056	**0.066**	325	**0.026**
38	Hansrivier 10	####	0.024	0.019	0.019	0.032	0.027	**0.032**	188	**0.015**
39	Hansrivier 12	####	0.006	0.005	0.005	0.007	0.007	**0.010**	31	**0.003**
40	Hansrivier 13	####	0.024	0.019	0.018	0.031	0.026	**0.030**	175	**0.014**
41	Hoenderhok	####	0.034	0.027	0.026	0.044	0.037	**0.045**	325	**0.026**
42	Saucyskuil	####	0.014	0.011	0.010	0.017	0.015	**0.019**	54	**0.004**
43	Olivegrove 03	####	0.019	0.015	0.014	0.024	0.021	**0.026**	164	**0.013**

🟦	Class 0 : Ideal water quality	Dose rate <= 0.10mSv/a	U: < 0.015 mg/l	Guideline (SANS 2011)
🟩	Class I: Good water quality	Dose rate: 0.10-0.25 mSv/a	U: < 0.070 mg/l	No significant risks. Annual cancer risk less than one in four million (DWAF 2002)
🟨	Class II: Marginal water quality	Dose rate: 0.250-1mSv/a	U: 0.070-0.284 mg/l	Annual cancer risk less than one in a million (DWAF 2002)
🟥	Class III: Poor water quality	Dose rate: 1-5mSv/a	U: 0.284-1.42 mg/l	Annual cancer risk less than one in 200 000 but significant risk of chemical toxicity with renal
🟪	Class IV: Unacceptable water quality	Dose rate: >5mSv/a	U: >1.42 mg/l	Increasing cancer risk in the long term (DWAF 2002)