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ANALYSIS OF NATURALLY OCCURRING RADIOACTIVE MATERIAL AND RADIOCESIUM IN SEDIMENTS FROM THE WONDERFONTEIN CATCHMENMT AREA IN THE NORTH-WEST PROVINCE AND MOSSES FROM MINSK (BELARUS) USING GAMMA SPECTROMETRY AND GAS-FLOW PROPORTIONAL COUNTING

BY

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A DISSERTATION IN PARTIAL FULFILLMENT OF THE REQUIREMENTS OF THE DEGREE OF MASTER OF SCIENCE IN APPLIED RADIATION SCIENCE AND TECHNOLOGY

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ABSTRACT

The mining and mineral processing activities around the Wonderfonteinspruit catchment area have been responsible for the discharge of waste into the stream for many years, causing the accumulation of radioactive nuclides in sediments. Afar a field, the Chernobyl nuclear power plant accident and other activities such as atmospheric nuclear explosions caused a huge distribution of fallout radioactive products into the environment especially from Minsk area in Belarus.

A large number of sediment samples collected in the catchment area and several mosses samples from the Minsk area were measured using high resolution gamma spectrometry for gamma measurements and gas-flow proportional counter for gross alpha-beta counting. Interference by other nuclides due to comparable photopeaks of interval has been corrected for.

All the natural decay chains have been assayed. The average ^{238}U determined from the ^{234}Th has been found to average 0.934 ± 0.014 Bq/g with median at 0.621 Bq/g. This is twice the legislated exemption level of 0.5 Bq/g. The average activity concentration for the ^{235}U (0.040 ± 0.004 Bq/g) is within the legislated exemption level. The average concentration for ^{232}Th of 75.4 mBq/g is well below the legislated exemption level. Radioactivity equilibrium between parent and daughter nuclides has been observed taking into account the 150 years sedimentation since the start of mining activities. No deposits of ^{134}Cs and ^{137}Cs have been observed in the catchment area but the activity concentrations of these nuclides are still detectable in the mosses from the Minsk (Belarus). The gross alpha-beta activities are well correlated with the gamma spectrometric results.

The potential radiological hazard to human has been projected taking into account all the sources of radioactivity. This may be through direct drinking of water from the catchment area by the communities living around it.

Declaration of Authenticity

I, the undersigned ISRAEL ITUMELENG RAMATLHAPE, hereby certify that the work presented in this dissertation except where otherwise indicated, is my own original work and has not been submitted to any university for the purpose of obtaining a degree.

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Pelindaba, 09 November 2009

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1. INTRODUCTION

1.1 Background and motivation

Radionuclides which are released to the environment are mobile to a certain extent that many can be accumulated in living organisms through the food chain. Approximately 80% of all human exposure comes from naturally occurring background radiation, but additional exposure due to ingestion of contaminated foodstuffs.

Sediments were sampled from the Wonderfonteinspruit, spreading over Gauteng and the North-West Provinces in South Africa, while mosses were sampled from Minsk in Belarus. These samples were analysed for Naturally Occurring Radioactive Material (NORM) and radiocesium. The Wonderfonteinspruit is located around mining and agricultural activities while Minsk was lately exposed to the Chernobyl accident.

Mining and mineral processing industries that are associated with NORM bare ore bodies which have the potential to increase the risk of radiation exposure to the environment and humans, by concentrating naturally occurring radiation beyond normal background levels. Besides NORM there is also the potential of nuclear fall-out due to incidental or accidental releases to the atmosphere from nuclear power generation. [31]

The survey and production of uranium in the Witwatersrand was initiated by the Manhattan project, with South Africa eventually becoming the 4th largest producer of uranium worldwide, with the vast majority of this being a by-product from the gold ores of the Witwatersrand Supergroup.[14] The high mobility of some of the NORM nuclides in the environment allows them to move and contaminate the environment with which humans come in contact.[12] Uranium in the gold mining areas can accumulate up to 1000 ppm in the sediments with an average concentration of about 100 ppm. [6]

Most natural radioactive elements are members of one of three NORM series, (i.e. the uranium, thorium and actinium series of which the parent nuclides are ^{238}U, ^{232}Th, and ^{235}U respectively) and also ^{40}K as part of the potassium content of the earth's crust. The concentrations of NORM in most cases are relatively low so that the risk is generally regarded as negligible; however, higher concentrations may occur as a result of the intervention of man in the environment (e.g. through mining and mineral processing).

The presence of NORM nuclides in the sediments of the entire Wonderfonteinspruit catchment area have been observed in a number of studies by Faanhof, the Department of Water Affairs and Forestry and the National Nuclear Regulator. [6, 9, 32, 40, 20] If concentrations are elevated over the entire catchment, this would be of great concern to the communities living in the catchment area, to farmers using the sediments as fertilizers and especially to the mineral and mining processing industries as the prime suspects of the pollution. Only the concentrations of uranium and thorium are currently known and it would be of great importance to know how much of their daughter nuclides are present, also to evaluate their possible impact on the public due to agricultural and life-stock products originating from these areas.

During the decay process of excited and fission related radionuclides, the mother radionuclides emit alpha and/or beta particles, and in the process create daughter nuclides that will emit their energy in the form of gamma-rays before decaying to another daughter nuclide. As not all daughter nuclides produce useful gamma-rays, it was not possible to quantify the activity concentration of all members of the NORM-series nuclides in this study.

Fission related radioactive nuclides such as the isotopes of caesium (e.g. ^{134}Cs and ^{137}Cs) have been released into the atmosphere as a result of nuclear weapon testing, accidents from nuclear reactors and nuclear-powered satellites blazing up in the atmosphere upon re-entry. [20] Caesium-137 in small quantities can still be found in the environment from nuclear weapons test that occurred in the 1950s and 1960s, and from nuclear reactor accidents, such as the Chernobyl power plant in 1986, which caused high fallout of radioactive caesium into the environment, especially in Europe and many parts throughout the Northern Hemisphere.[8]

According to the data published in the Government Gazette of 28 April 2006, materials are excluded from regulations if the level of radioactivity per individual radionuclide of the naturally occurring radioactive nuclides of the uranium, thorium, and actinium series does not exceed 0.5 Bq per gram. For artificial nuclides the radioactivity levels should not exceed 0.2 Bq per gram and for potassium-40, the levels should not exceed 10 Bq per gram in building construction or disposal and 50 Bq per gram in any other material (which is a flaw in the legislation as this could only occur in ^{40}K-enriched materials, which are unlikely to be found in nature or be man-made; the maximum ^{40}K activity of pure potassium metal is 33 Bq/g).

1.2 Problem Statement

The longer-lived radionuclides such as ^{238}U, ^{235}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Pb, ^{231}Pa, ^{227}Ac and ^{232}Th settle in sediments and mosses in the formation of peat and could exist in the environment for long periods, meanwhile coming into contact with humans. Short-lived radionuclides such as ^{134}Cs would only be a problem for a short period of time, but ^{137}Cs would still cause problems as it decays with a half-live of 30 years.

Accumulation of radioactivity in sediments and mosses could cause internal exposure to humans if used for agricultural purposes (e.g. sediments and mosses used as peat-fertilizer to grow fruits, vegetables or used for cattle grazing). ^{137}Cs and NORM nuclides in water, milk, meat, vegetables and other foodstuffs would be the major contributor to the internal dose received by humans over long periods of exposure.

Mining and mineral processing activities occur in the study area and waste tailings or waste rock dumpings are formed. Nuclides can be remobilized and get into the environment due to a variety of oxidation-reduction processes. Uranium, in particular, is easily mobilized in surface water. As a result, uranium can enter the food chain through direct intake or through produce irrigated with contaminated waters. It will normally not enter tap-water supplies through surface-water streams and rivers as these waters are normally purified (filtration/flocculation) before being released to the

system. Elevated concentrations of radioactivity in the environment would pose a health risk to humans, but the level of risk involved is not clearly defined because not enough is known about the distribution and concentration of these radioactive nuclides in the environment.

1.3 Research Objectives

The main objective of the research is to determine and evaluate the concentrations of naturally occurring radioactive and fission related radionuclides in around 250 sediment samples from the southern part of the Wonderfonteinspruit catchment and 10 mosses from the Minsk area in Belarus. The use of gamma spectrometry and gas-flow proportional counting methods have been chosen to get a picture of some specific radionuclides and the overall alpha and beta activity to evaluate the possibility of additional nuclides not measured by gamma spectrometry. From the data obtained a preliminary evaluation was been done on the potential radiological impact on humans through the release of radionuclides from the sediments to the water body that can be used by local communities for drinking purposes.

The study was scheduled as follows:

- The activity concentrations of gamma-emitting NORM and fission related nuclides in the sediments and mosses were measured
- Both gas-flow proportional alpha/beta activity results and the gamma-spectrometric data were compared, and the cause of possible discrepancies are discussed, and
- The possible radiological impacts on humans through the ingestion of foodstuffs grown in the contaminated areas were evaluated.

Cesium-137 and cesium-134 are not expected to be concentrated much in the sediments from the Wonderfonteinspruit compared to the mosses from the Minsk area, while the vice versa is expected for the NORM nuclides.

2. THEORETICAL BACKGROUND

2.1 NORM (Naturally Occurring Radioactive Material) in the environment

2.1.1 Uranium, Thorium and Potassium

2.1.1.1 Introduction

Natural sources of radiation derived from radioactive elements that were synthesised in the formation of the solar system have been deposited in some amounts in the earth's mantle and eventually are found in the tissues of every living being, also in man. Standard earth crust abundances of these elements quoted in the literature are in the range 1.5-2.5% potassium, 2-3 ppm uranium, and 8-12 ppm thorium.[1] These still exist because of their very long half-lives.

^{238}U, ^{235}U, and ^{232}Th are the parents of the three natural decay series, called the uranium series, the actinium series and the thorium series, respectively. These series each consist of many radioactive daughter nuclides generated through successive decay of the parent radionuclides.

2.1.1.2 Uranium

Uranium in nature is a combination of the isotopes ^{238}U (99.28%), ^{234}U (0.0058%), and ^{235}U (0.72%). There is, therefore, about 138 times more ^{238}U than ^{235}U in a natural sample in mass comparison, but due to the difference in half-lives their activity ratio is about 21:1. Chemical specific characteristics such as precipitation/dissolution and sorption, as well as physical characteristics such as particle deposition/suspension and weathering of host minerals affect the aqueous concentration and mobility of nuclide.[2] The decay series daughter products are also significantly affected by processes such as decay, sorption and alpha recoil.[2]

The mass ratio of ^{238}U to ^{234}U is about 18 000.[24] However, ^{238}U decays to its daughter product ^{234}U and in the host mineral these isotopes are in radioactive equilibrium, that is $^{238}U/^{234}U$ activity ratio equals 1. The $^{238}U/^{234}U$ activity ratio is usually less than one in natural waters due to one alpha and two beta recoils to form the ^{234}U daughter product from ^{238}U. Accordingly, ^{234}U will be less strongly bound in the original ore lattice and becomes more mobile and prone to leaching from the host mineral, which lowers the $^{238}U/^{234}U$ activity ratio in the aqueous phase.[10]

Uranous, U(IV), and uranyl, U(VI), are the oxidation states of uranium mainly observed in the environment. Uranium, as the UO_2^{2+} uranyl ion, is reasonably mobile in the subsurface and may travel until it encounters conditions which are reducing. At this point, reduction of U (VI) may lead to precipitation of uranium minerals such as uraninite, coffinite, or brannerite.[2]

2.1.1.3 Thorium

Natural thorium occurs mainly as the isotope ^{232}Th, exceeding 99%.[25] Thorium occurs naturally as Th(VI), which has a low solubility and tends to adsorb very strongly to mineral/solid surfaces and accordingly has low mobility and is not easily leached from the mineral ores by ground or surface water. The aqueous concentration of thorium is inhibited by the formation of sparsely soluble thorium oxyhydroxides or oxides.[2] It is moved from one place to another by human and natural causes, that is

due to mining and mineral processing activities or when rocks erode naturally from where it can be washed into rivers and lakes.[25] Thorium decays very slowly (half-live of 1.4×10^{10} years).

2.1.1.4 Potassium

Potassium-40 occurs naturally as a radioactive isotope with an abundance of about 0.012% of the natural potassium found in the earth's crust, oceans, and organic matter. The half-life of ^{40}K is about 1.3×10^9 years and decays to ^{40}Ca by emitting a beta particle with no attendant gamma radiation (89% of the time) or to ^{40}Ar by electron capture followed by the emission of an energetic gamma ray (11% of the time).[26]

About 15 000 mg/kg or 1.5% of potassium is concentrated in the earth's crust while ^{40}K is only approximately 1.8 mg/kg, which is equivalent to about 0.48 Bq/g. Potassium contributes significantly to the fertility of the soil and it is an important nutrient for plant growth and the human diet.[1]

2.1.2 Decay Series

The respective nuclides in the uranium, actinium and thorium series' decay chains with their half-lives, mode of decay and gamma energies and intensities[1] are given in Tables 2.1, 2.2 and 2.3 respectively. Table 2.4 sums-up the long-lived nuclides in each of the three series.[40]

Uranium occurs in nature as radioisotopes $^{238}U/^{234}U$ and ^{235}U giving rise to the decay series that end in the stable isotopes ^{206}Pb and ^{207}Pb (Tables 2.1 and 2.2). The half-lives of ^{238}U and ^{235}U are 4.46×10^9 and 7.13×10^8 years, respectively. The decay of ^{238}U to ^{206}Pb results in the emission of eight alpha particles and six beta particles while that of ^{235}U to ^{207}Pb results in seven alpha and four beta particles. Thorium naturally occurs as the radioisotope ^{232}Th, which decays to ^{208}Pb resulting in six alpha and four beta particles (Table 2.3). Thorium's (^{232}Th) half-life is 1.39×10^{10} years and neither ^{232}Th nor ^{238}U do release gamma rays but the gamma ray emissions from their direct radioactive daughter products can be used to estimate their concentrations. This also holds for other long-lived nuclides not emitting suitable gamma-rays. Since ^{40}K of 1.3×10^9 years half-life occurs as a fixed percentage of potassium in the natural environment its gamma rays can be used to determine the total amount of potassium present.

Thorium hardly ever occurs out of equilibrium in nature, and potassium has no disequilibrium inconvenience.[25] However, in the decay series of uranium, disequilibrium is common, and might occur at numerous positions in the ^{238}U decay series. The ^{235}U and ^{238}U have a fixed ratio in nature and accordingly ^{235}U can be used to determine the uranium content of a sample.[2] This, however, needs again a correction for the ^{226}Ra content of the sample as they have gamma energies close to each other which can not be differentiated between by the spectrometric analysis. This correction can be obtained from the measurements of ^{214}Bi and ^{214}Pb, taking re-equilibration into consideration which again can be influenced due to the possible loss of radon.

The mobility of some radionuclides in the mixture with sediments and mosses in the decay chains may be limited because of their chemical properties therefore remaining relatively undisturbed for over a long period of time. In this case, these radionuclides in the decay series may be said to be in secular equilibrium, meaning that all radionuclides in a given decay sub-chain may have similar activity values. However, the longer-lived radionuclides which may have been deposited and/or absorbed from the environment in different quantities and accordingly the equilibrium of the entire chain should not be expected.

Table 2.1 ^{238}U decay series

Nuclide	Half-life	Major Gamma Radiation Energies (MeV) and Intensities
^{238}U	4.5×10^9 a	0.049 (0.064%)
↓ α		0.113 (0.0102%)
^{234}Th	24.1 d	0.063 (3.5%)
↓ β		0.093 (4%)
^{234m}Pa	1.18 min	0.765 (0.30%)
(99.86%) ↓ β		1.001 (0.84%)
^{234}U	2.38×10^5 a	0.053 (0.2%)
↓ α		
^{230}Th	7.52×10^4 a	0.068 (0.6%)
↓ α		0.142 (0.07%)
^{226}Ra	1602 a	0.185 (4%)
↓ α		
^{222}Rn	3.825 d	0.510 (0.07%)
↓ α		
^{218}Po	3.05 m	No gamma
↓ α		
^{214}Pb	26.8 m	0.295 (19%)
↓ β		0.352 (36%)
^{214}Bi	19.7 m	0.609 (47%)
(99.98%) ↓ β		1.120 (17%)
		1.765 (17%)
^{214}Po	164 µs	0.799 (0.014%)
↓ α		
^{210}Pb	22,3 a	0.047 (4%)
↓ β		
^{210}Bi	5.02 d	0.266 (50%)
↓ β		0.305 (28%)
^{210}Po	138.3 d	0.803 (0.0011%)
↓ α		
^{206}Pb	stable	

Minor branchings omitted

Table 2.2 ^{235}U decay series (Actinium series)

Nuclide	Half-life	Major Gamma Radiation Energies (MeV) and Intensities
^{235}U ↓ α	7.13×10^8 a	0.143 (10.96%) 0.185 (54%) 0.204 (5.01%)
^{231}Th ↓ β	24.64 h	0.026 (2.0%) 0.084 (10%)
^{231}Pa ↓ α	3.43×10^4 a	0.027 (6%) 0.029 (6%)
^{227}Ac (98.8%) ↓ β	21.8 a	0.070 (0.08%)
^{227}Th ↓ α	18.17 d	0.050 (8%) 0.236 (15%) 0.31 (8%)
^{223}Ra ↓ α	11.68 d	0.149 (10%) 0.270 (10%) 0.33 (6%)
^{219}Rn ↓ α	3.92 s	0.272 (9%) 0.401 (5%)
^{215}Po ↓ α	1.83 ms	No gamma
^{211}Pb ↓ β	36.1 m	0.405 (3.4%) 0.427 (1.8%) 0.832 (3.4%)
^{211}Bi (98.7%) ↓ α	2.16 m	0.351 (14%)
^{207}Tl ↓β	4.79 m	0.897 (0.16%)
^{207}Pb	stable	

Minor branchings omitted

Table 2.3 ^{232}Th decay series

Nuclide	Half-life	Major Gamma Radiation Energies (MeV) and Intensities
^{232}Th ↓ α	1.39×10^{10} a	0.064 (0.263%) 0.141 (0.021%)
^{228}Ra ↓ β	5.75 a	0.0135 (1.6%) 0.015 (3%)
^{228}Ac ↓ β	6.13 h	0.340 (15%) 0.908 (25%) 0.960 (20%)
^{228}Th ↓ α	1.913 a	0.084 (1.6%) 0.216 (0.3%)
^{224}Ra ↓ α	3.64 d	0.241 (3.7%)
^{220}Rn ↓ α	55.6 s	0.550 (0.07%)
^{216}Po ↓ α	0.14 s	0.805 (0.0019%)
^{212}Pb ↓ β	10.64 h	0.239 (47%) 0.300 (3.2%)
^{212}Bi → (36%) (64%) ↓ β ↓ α	60.5 m	0.040 (2%) 0.727 (7%)
^{212}Po ↓ ↓ α	304 ns	1.620 (1.8%)
^{208}Tl ↓ ↓ β	3.1 m	0.583 (84.5%) 2.614 (99.14%)
^{208}Pb ←	Stable	

Minor branchings omitted

Table 2.4 Long-lived natural radionuclides and half-lives [40]

^{238}U series		^{235}U series		^{232}Th series	
^{238}U	4.5×10^{9} a				
^{234}U	2.38×10^{5} a	^{235}U	7.13×10^{8} a	^{232}Th	1.39×10^{10} a
^{230}Th	7.54×10^{4} a	^{231}Pa	3.43×10^{4} a	^{228}Ra	5.75 a
^{226}Ra	1602 a	^{227}Ac	21.8 a	^{228}Th	1.9 a
^{210}Pb	22.3 a				

2.1.3 Useful gamma energies of uranium, actinium and thorium chain nuclides

Direct measurements of ^{238}U are unlikely in the environmental samples, since it is a very poor gamma emitter. The gamma energy line of ^{238}U is 49.5 keV with a very low (0.064%) intensity. However, the assumption of secular equilibrium, enables the determination of ^{238}U from its direct daughter ^{234}Th, on the 63.3 keV (4.8 %) gamma line, which is a fair assumption regarding the origin of the sample and the relative short half-life of ^{234}Th of 24.1 days. However, interference from ^{232}Th may occur, only if samples contain much more thorium than uranium (about 20% interference at a Th/U ratio of 4, which is unlikely in a natural uranium rich environment).

^{234}U, at 53.2 keV has a small emission probability of 0.123%. Interference can be expected from the ^{214}Pb line at 53.2 keV with a probability of 1.07%. Again the 351.9 keV or 295.21 keV line of ^{214}Pb can be used for corrections, although this will increase the uncertainty in the measurement substantially.

Since ^{235}U energy line of 185.7 keV (at 57.25%) is interfered by 186.2 keV (at 3.59%) line of ^{226}Ra, an alternative gamma line can be considered. The 143.76 keV energy line of ^{235}U with 10.96% emission probability may be used. Corrections can be made if the 143.7 keV line of ^{235}U is also detected (10.96% probability), otherwise the ^{222}Rn daughters of; ^{214}Pb (351.9 keV, 37.6%) and ^{214}Bi (609.3 keV, 46.1%) provide the option for corrections if equilibrium over ^{222}Rn can be assured as radon may have escaped during sample preparation. [28]

^{228}Ra can be measured indirectly by using the energy line of its daughter ^{228}Ac at 911.2 keV with 25.8 % intensity. ^{228}Th has a weak (1.22 %) line at 84.4 keV, but one can use its daughters ^{212}Pb at 238.6 keV with a 44.7 % emission probability and ^{212}Bi at 727.27 keV with emission of 11.8 %. No emanation problems of the ^{220}Rn daughter are expected due to its short half-life of 55.6 s.

The detailed analytical library used in this investigation for the gamma-ray spectrometry is given in Table 2.5 together with the potential interfering nuclides, emitted gamma energies and ther intensities (or emission probabilities).

Table 2.5 Nuclide library used and possible interferences (1MeV = 1000 keV)

	Nuclide	Half-life	Energy line (keV)	Intensity (%)
1	^{231}Th	25.52 h	19.1	3.7
2	^{235}U	7.038×10^{8} a	19.59	61
3	^{231}Pa	32760 a	25.51	0.117
4	^{231}Th	25.52 h	25.64	14.5
5	^{231}Pa	32760 a	46.35	0.223
6	^{210}Pb	22.3 a	46.539	4.25
7	^{238}U	4.468×10^{9} a	49.55	0.064
8	^{227}Th	18.72 d	49.89	0.57
9	^{227}Th	18.72 d	50.13	8
10	^{231}Pa	32760 a	52.73	0.085
11	^{234}U	245500 a	53.2	0.1232
12	^{214}Pb	26.8 m	53.2275	1.2
13	^{234}Th	24.1 d	63.29	4.8
14	^{232}Th	1.405×10^{10} a	63.81	0.263
15	^{230}Th	75380 a	67.672	0.38
16	^{231}Th	25.52 h	84.214	6.6
17	^{228}Th	1.912 a	84.373	1.22
18	^{234}Th	24.1 d	92.38	2.8
19	^{234}Th	24.1 d	92.8	2.8
20	^{234}U	245500 a	120.9	0.0342
21	^{228}Ac	6.15 h	129.065	2.42
22	^{219}Rn	3.96 s	130.59	0.119
23	^{223}Ra	11.435 d	131.2	0.005
24	^{228}Th	1.912 a	131.613	0.1305
25	^{235}U	7.038×10^{8} a	142.4	0.005
26	^{235}U	7.038×10^{8} a	143.76	10.96
27	^{230}Th	75380 a	143.872	0.049
28	^{223}Ra	11.435 d	144.232	3.22
29	^{228}Ac	6.15 h	153.977	0.722
30	^{223}Ra	11.435 d	154.21	5.62
31	^{223}Ra	11.435 d	158.633	0.685
32	^{235}U	7.038×10^{8} a	163.33	5.08
33	^{235}U	7.038×10^{8} a	185.715	57.2
34	^{230}Th	75380 a	186.053	0.008787
35	^{226}Ra	1600 a	186.211	3.59
36	^{235}U	7.038×10^{8} a	205.311	5.01
37	^{228}Ac	6.15 h	214.85	0.029
38	^{235}U	7.038×10^{8} a	215.28	0.027
39	^{228}Th	1.912 a	215.983	0.254
40	^{231}Th	25.52 h	217.94	0.04
41	^{227}Th	18.72 d	234.81	0.41
42	^{227}Th	18.72 d	235.971	12.3
43	^{212}Pb	10.64 h	238.632	43.3
44	^{235}U	7.038×10^{8} a	240.87	0.075
45	^{224}Ra	3.66 d	240.986	4.1
46	^{227}Ac	21.773 a	241.7	0.001628
47	^{214}Pb	26.8 m	241.997	7.43
48	^{227}Th	18.72 d	254.68	0.7
49	^{227}Th	18.72 d	256.25	7

Table 2.5 Nuclide library used and possible interferences (continued)

	Nuclide	Half-life	Energy line (keV)	Intensity (%)
50	^{223}Ra	11.435 d	269.459	13.7
51	^{228}Ac	6.15 h	270.245	3.46
52	^{227}Th	18.72 d	270.7	0.037
53	^{219}Rn	3.96 s	271.23	10.8
54	^{227}Th	18.72 d	272.93	0.48
55	^{214}Pb	26.8 m	295.224	19.3
56	^{227}Th	18.72 d	296.51	0.46
57	^{227}Th	18.72 d	300	0.34
58	^{227}Th	18.72 d	300	2.3
59	^{231}Pa	32760 a	300.07	2.47
60	^{212}Pb	10.64 h	300.087	3.28
61	^{231}Pa	32760 a	302.65	0.68
62	^{231}Pa	32760 a	302.65	2.2
63	^{227}Th	18.72 d	304.519	1.2
64	^{228}Ac	6.15 h	321.646	0.226
65	^{223}Ra	11.435 d	323.871	3.93
66	^{223}Ra	11.435 d	338.281	2.79
67	^{228}Ac	6.15 h	338.32	11.27
68	^{211}Bi	2.14 m	351.06	12.91
69	^{231}Pa	32760 a	351.51	0.00731
70	^{214}Pb	26.8 m	351.932	37.6
71	^{219}Rn	3.96 s	401.81	6.4
72	^{211}Pb	36.1 m	404.853	3.78
73	^{214}Bi	19.9 m	405.74	0.17
74	^{208}Tl	3.053 m	510.77	22.6
75	^{212}Po	45.1 s	570	1.9986
76	^{228}Ac	6.15 h	570.91	0.182
77	^{208}Tl	3.053 m	583.191	84.5
78	^{228}Ac	6.15 h	583.41	0.111
79	^{214}Bi	19.9 m	609.312	46.1
80	^{137}Cs	30.04 a	661.66	85.10
81	^{228}Ac	6.15 h	726.863	0.62
82	^{212}Bi	60.55 m	727.33	6.58
83	^{234m}Pa	1.17 m	766.36	0.294
84	^{211}Pb	36.1 m	766.51	0.617
85	^{134}Cs	2.0648 a	795.864	85.40
86	^{214}Po	164.3 µs	799.7	0.01035
87	^{211}Pb	36.1 m	832.01	3.52
88	^{208}Tl	3.053 m	860.564	12.42
89	^{207}Tl	4.77 m	897.77	0.26
90	^{228}Ac	6.15 h	911.204	25.8
91	^{214}Bi	19.9 m	964.08	0.362
92	^{228}Ac	6.15 h	964.766	4.99
93	^{228}Ac	6.15 h	968.971	15.8
94	^{234m}Pa	1.17 m	1001.03	0.837
95	^{214}Bi	19.9 m	1120.287	15.1
96	^{40}K	1.277×10^{9}a	1460.81	10.67
97	^{214}Bi	19.9 m	1764.494	15.4
98	^{212}Po	45.1 s	2610	2.6
99	^{208}Tl	3.053 m	2614.533	99.16

2.2 Types of radiation

2.2.1 Introduction

The radioactive nuclides of the three decay series decay either by emitting alpha and/or beta particles accompanied, in some cases, by gamma radiation. Each of these will be briefly discussed.

2.2.2 Alpha particles

The alpha particle is a helium nucleus (^{4}He) consisting of two protons and two neutrons. Large parts of each of the series emit alpha particles (Tables 2.1, 2.2 and 2.3). These particles have a high energy between about 3 000 to 10 000 keV and accordingly will damage human cells if they are exposed to them directly, that is through intake. Externally, alpha radiation can be stopped by the top layer of skin or a few centimeters of air and accordingly does only pose a risk when deposited on the skin.

2.2.3 Beta particles

Beta particles are in fact electrons (or a positron in case of a β^+), which travel at high speeds when emitted from the decaying nucleus. These electrons interact with energies of 5 keV to 4 000 keV which cause inelastic scattering by atomic electrons, elastic nuclear and electron scattering, and radiative interactions with nuclei and atomic electrons

They are smaller and have less energy compared to alpha particles but have a larger range travelling through material. Beta particles therefore can pass through the outer layer of the skin and strike the cells below. Upon intake they can also damage cells but less severe than alpha particles cause of the difference in the masses (heaviness) of these particles.

2.2.4 Gamma rays

Gamma radiation is in fact electromagnetic radiation and for NORM nuclides range between 10 and 2600 keV. They travel at the speed of light (c), and have a discreet energy (E), frequency (f), and wavelength (λ). [1] These are related by:

$$E = hf = hc/\lambda$$

where h = Planck's constant 6.6261×10^{-34} Js;

c = velocity of light.

Gamma rays interact with atoms of material by three major processes. These processes are the photoelectric effect, Compton scattering and pair production. The photoelectric effect occurs at lower energies, and results in all of the energy of a gamma quantum being absorbed on impact with an electron of an atom. Compton scattering mainly takes place at moderate energies and correspond to an impact of an incident photon with an electron whereby part of the energy is conveyed. The incident photon loses a fraction of its energy to the electron and is "scattered" at an angle to its original direction. Pair production predominates at energies more than 1.02 MeV. It is

the process whereby an incident photon is completely absorbed and results in the creation of an electron-positron pair in the electrostatic field of a nucleus. (1)

Each gamma ray photon has a discreet energy, and this energy has characteristics of the source isotope. This forms the basis of gamma ray spectrometry. By measuring the energies of gamma ray photons, the source of radiation can be determined. Typically, gamma ray photons lose energy through successive Compton scattering events, until eventually the resulting low-energy photons are absorbed through the photoelectric effect. (1) The interaction of gamma rays with matter results in the intensity of radiation lessening with distance from source.

Gamma rays penetrate the material much easier than either an alpha or beta particle, becoming an external radiation risk. However, internal exposure to gamma-emitting radioactive substances will still be hazardous.

2.3 Fission related radioactive nuclides

There are a large number of nuclides with different half-lives which are released to the atmosphere when fission take place during atmospheric weapons testing, accidents from nuclear reactors and nuclear-powered satellites burning up in the atmosphere upon re-entry.(21)

The accident at the Chernobyl nuclear power plant resulted in the release of an initially estimated 2.0×10^{16} Bq (5.4×10^{5} Ci) of ^{134}Cs and 4.0×10^{16} Bq (1.1×10^{6} Ci) of ^{137}Cs into the atmosphere over Europe. (21) Further current estimates have put the total activity of ^{137}Cs and ^{134}Cs released from the Chernobyl power plant as 8.5×10^{16} Bq (2.3×10^{6} Ci) and 4.4×10^{16} Bq (1.2×10^{6} Ci) respectively. (29)

^{137}Cs is a radioactive isotope which is formed mainly by nuclear fission. It has a half-life of 30.23 years and disintegrates by pure beta (-) decay to ^{137}Ba. The energy of the gamma rays of ^{137}Cs is 661.76 keV, with an absolute intensity of 85.1%.

^{137}Cs is water-soluble and extremely toxic in large concentrated amounts. Released into the environment, ^{137}Cs remains present for many years due to its long radiological half-life of 30.1 years. It can cause cancer 10, 20, or 30 years from the time of ingestion, inhalation or absorption providing sufficient material enters the body. (16)

^{134}Cs has a half-life 2.065 years and disintegrates mainly via beta (-) emission and has many gamma energies, of which the most useful for detection are the lines 604.7 keV, 795.9 keV, and 569.3 keV, with absolute intensities of 97.6%, 85.5%, and 15.4% respectively.

The presence of ^{137}Cs and ^{134}Cs in mosses from the Minsk area (and to a far lesser extent in the sediment samples from the Wonderfonteinspruit) can be from several origins:

- Delivered by global fallout as a result of release from atmospheric nuclear weapons testing. It was introduced into the environment in significant quantities from 1954 and the fallout peaked in 1963;
- From the Chernobyl accident (April 26, 1986), when the recent ^{137}Cs and ^{134}Cs were introduced in the atmosphere.

2.4 Radioactivity in the environment

2.4.1 Sediments

2.4.1.1 Sedimentation properties

River sediments vary in size from particles in the clay- and silt-size range to coarser sands and gravel. Vegetation by the river also serves to trap sediments that are probably washed in from adjacent fields. Because of internal river mixing (mixture of plant material, debris and decomposed organic matter), sediments in deeper areas tend to be finer and higher in organic content than the lower littoral sediments. River sediments are thus accessible to contamination from atmospheric and hydrological sources. [6]

The role of sedimentation depends on the size of the particulate, the rate and type of flow through the wetlands, and the residence time of the particulate. The wetlands with dense stands of vegetation also enhance sedimentation by decreasing the velocity of water flowing through them. The adsorption/desorption processes allows pollutants to be redistributed to suspended particulate, bottom sediments and vegetation. [6]

The understanding of factors affecting the transport and bioavailability of radioactive nuclides in rivers is important to predict their fate in freshwater systems. The mechanism whereby radioactive nuclides are removed from water to sediment is very important as these nuclides could combine with sediments reducing their mobility and bioavailability. [6]

Sediments play an important role in the assessment of the contamination in natural waters as they have a high capacity to accumulate and integrate over time the low concentration of radionuclides in water. Therefore, sediments from minerals allow the determination of pollutants even when the levels of water in extremely low and undetectable with current methods of analysis. The enrichment rate of pollutants in river sediment reflects the upstream contamination sources and the interesting characteristic of the sediments lies in the ability of its compartments to trap radionuclides. [10]

Sediment particles are both physical supporters and carriers of numerous contaminants in the natural waterways. They can act as a sink; the settling of suspended material is clearly one of the most important processes, which effectively removes contaminants adsorbed to the particles from the river. [13] These pollutants are then not directly obtainable for transfer to man. Sediments can be considered as an accumulation compartment where large amounts of contaminants are stored or a site where radioactive products are deposited.

Radionuclides are concentrated in sediments downstream of their sources. Sequential extractions show that these radionuclides are distributed in multiple phases within the sediments and that they may be remobilised by environmentally plausible chemical processes. [6]

Mining and mineral processing contribute to a wide range of water problems; the use of contaminated sediments as fertilizers is a global issue that tends to be primarily associated with agriculture. A more than a century old mining activity around the catchment area would be equivalent to approximately the

first two meters of sediments, which accounts for around the last 125 years of sedimentation.

2.4.1.2 NORM in sediments

The Wonderfonteinspruit and its tributaries pass through the authoritative districts of Potchefstroom, Welverdiend, Oberholzer, Westonaria, and Randfontein (Figure 2.1). A few expanding communities are found along the catchment, that is, Kagiso, Mohlakeng, Toekomsrus, Rietvallei and Bekkersdal. These settlements, as well as the developments along the catchment, add to the discharge of pollution (e.g. sewage) into the surrounding waters. [6] The mining reefs surrounding the Wonderfonteinspruit catchment area include Carbon Leader, Middlevlei reef, White reef, Monarch reef, Elsburg reef, Composite reef, Ventersdorp Contact reef, and the Black reef. [6]

The eastern catchment of the river was identified in a number of studies as the site of significant radioactive and other pollution, generally attributed to the mining and processing of uraniferous gold ores in the area. [6] The Far West Rand was the first goldfield in South Africa where large-scale uranium production was established. The mined reefs contain not only gold, but also high concentrations of uranium (up to 5.8%). [6]

Preliminary monitoring by the Institute for Water Quality Studies (IWQS) of the Department of Water Affairs and Forestry done in 1995/97 showed that activity concentrations of radioactive elements in surface and ground waters were elevated in the Wonderfonteinspruit. [36] Since then some further studies in the Wonderfonteinspruit catchment area have been done. [6, 9] Due to the lack of funding only limited studies were done on the sediments in the region.

Figure 2.1 Krugersdorp and Potchefstroom area map

Coetzee et al. [6] observed that the sediments in the Upper and Lower Wonderfonteinspruit are characterised by the following:

1. The headwaters in non-dolomitic regions are slime and evaporate in filled dams with very elevated uranium concentrations (>1000 mg/kg in places).
2. Downstream wetlands of Kagiso are fine-grained organic-sludge uranium tailings concentrations without deposition from tailings. Uranium concentrations in this area may exceed 100 mg/kg.
3. Coarser stream sediments from Donaldson dam with uranium concentrations about 50 to 60 mg/kg, nearly similar to flood deposits sampled after the February 2000 rain event.
4. Downstream Donaldson dam the river is contained in a pipeline over dolomite for approximately 30 km. Sediments were last in regular contact with stream water approximately 30 years ago where uranium concentration of 12 mg/kg has been recorded for top soil sampled in the floodplain area. This area will occasionally be flooded with rainwater where a high degree of dilution is expected.
5. At the end of the pipeline a large volume of water, including a significant component of pumped mine water, is discharged into the catchment. Sediment uranium concentrations reach as much as ~500 mg/kg or more.
6. In downstream farm dams uranium concentrations are significantly elevated relative to the local background recorded at the Klerkskraal dam ([U] < 1 mg/kg). In one specific dam concentrations of up to 900 mg/kg have been recorded in the sediments.

The difference in sources of radionuclides (mine waters and slimes dams), their different geochemical and transportation behaviour in the environment, and variations in the source extension (intermittent mine water discharges, infrequent seepage water emission, and sporadic erosion from slimes dams after heavy rainfalls) were contributing contamination factors. A chronological and spatial discrepancy of the contamination levels and the activity ratios of various radionuclides in water and sediments observed. [14]

The reddish areas in the aerial survey shown in Figure 2.2 indicate elevated concentrations of radioactive materials in the wetlands of the Wonderfonteinspruit catchment area. [6] These high radioactivity levels occur mainly due to the surrounding mining activities (the big red spots are the mine tailings dams).

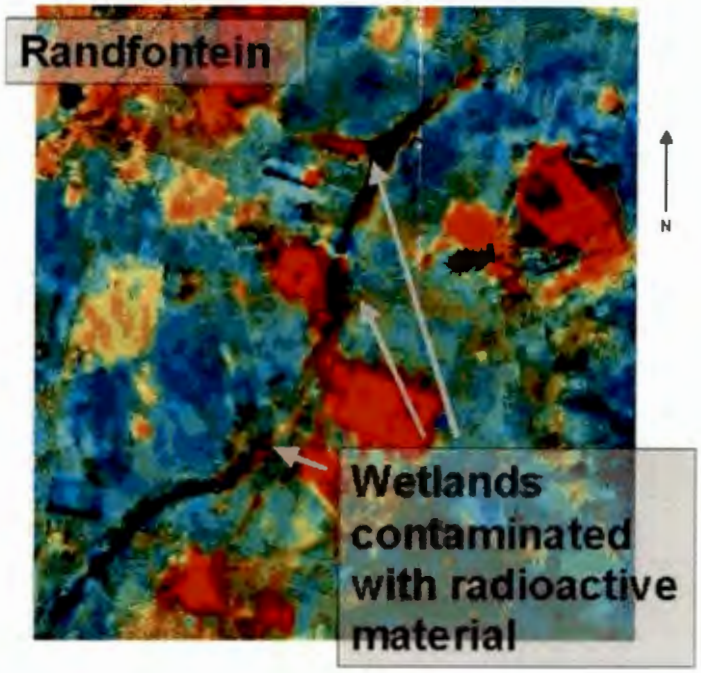

Figure 2.2 Radiometric image of the Wonderfonteinspruit catchment area [6]

Based on the observations it was concluded Coetzee et al [6] that,

- Large amounts of uranium (several tons per annum) enter the Wonderfonteinspruit via point releases and large-scale diffuse releases;
- Fluvial sediments of the river system and the local groundwater systems contain elevated levels of uranium, and
- The process whereby the mobility of uranium comes to a halt and settles in the sediments is irreversible.

Research done at South African gold mines reported that as a first order approximation up to 70% of the chemical contamination observed in the mine water discharged into the environment was from the pyritic oxidation processes in underground tunnels. [1]

Various pathway mechanisms whereby contaminants spread from their sources and enhance the NORM (and other pollutants) concentrations can be identified. Mine tailings and processed water eventually end up in the river system by erosion processes (i.e. wind and water erosion). The solid particles of these contaminants in the water settle in the bottom sediment where they are accumulated over a period of time until they are re-suspended due to turbulences causing movement of these particles from one point to another. The mechanism whereby sediments are displaced from the source decreases the uranium concentrations with increasing distance, implying that uranium is immobilized during the transportation. [6] A schematic overview is presented in Figure 2.3.

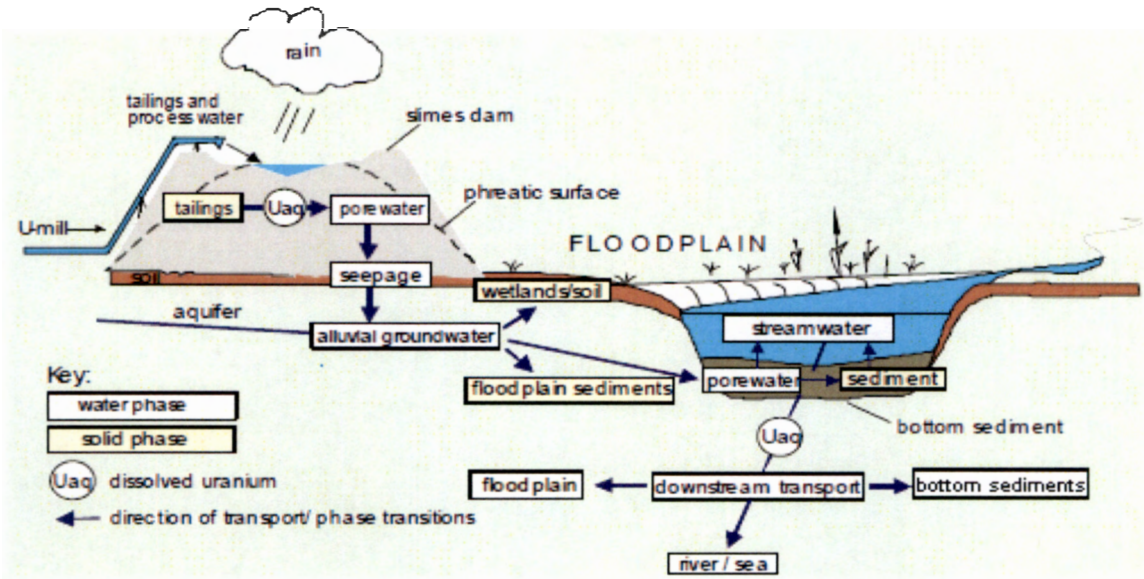

Figure 2.3 Schematic conceptual of site model [6]

The National Nuclear Regulator (NNR) reported in a study on the Wonderfonteinspruit catchment area in 2007 about the radiological impact of the mining activities to the surrounding public. [9] Sediment and water samples were analysed for NORM using high resolution gamma spectrometry and alpha spectrometry. Thirty eight (38) sediment samples were analysed and the specific activity reported. Table 2.6 shows the mean activity of NORM for the sediments from the NNR document.

Table 2.6 Mean specific activities of 38 sediment samples from an NNR study

Nuclide	Mean activity (Bq/g)
^{238}U	1.29 ± 0.03
^{230}Th	0.80 ± 0.04
^{226}Ra	0.82 ± 0.02
^{210}Pb	0.73 ± 0.02
^{235}U	0.060 ± 0.002
^{231}Pa	0.034 ± 0.012
^{227}Ac	0.041 ± 0.004
^{228}Ra	0.044 ± 0.001
^{228}Th	0.048 ± 0.001

From the table it can be observed that uranium is elevated in sediments. The radioactivity equilibrium of ^{230}Th, ^{226}Ra and ^{210}Pb from the uranium series, ^{231}Pa and ^{227}Ac from the actinium series and, ^{228}Ra and ^{228}Th from the thorium series resulted indicating the influence of either background and/or run-off tailings from the waste

dams. The activity ratio between ^{235}U and ^{238}U in natural uranium is 0.046 (1:21.7), which is also mirrored in the results. The same observation was made by Faanhof and Kempster [41] on data obtained by both radiochemical and ICP-MS analyses on water samples from the Mooi River catchment.

2.4.1.3 Adsorption of metals in sediments

Adsorption can be explained as the concentration of constituents at the colloidal surface. In the case of river sediments, heavy metals in water move freely through the pores of the sediments by gravity and capillary action. This process of drainage has negative effects, such as the leaching of NORM and other pollutants. [15] Contamination could later occur to the underground water resources.

Many heavy metals occur in the form of cations. The accumulation on sediment particles is based on their negative charge where clay colloids carry a negative charge and thus making it possible for cations to be attracted by clay particles in the sediment mixture.[6] Cations mostly occur in the liquid phase (i.e. water) and this makes it easier for cations to be transferred to pores of sediments. A general rule to apply if assessing preference of adsorption of cations is that the smaller the hydrated size of the metal ions, the better chance they will have to be adsorbed. [15]

The exchange of ions occurs when counter ions balancing the surface charge on the sediment particles exchange with the metal ions in the sediment solution. The cation exchange properties of sediments make it a good medium for adsorbing metals. If the cation exchange capacity of the sediment is reached, the pollution will migrate through it without being adsorbed. It sometimes takes a long time to reach this stage, which also depends on the acidity (pH) of the environment. The pH of the sediments, however, may not be fixed due to the heterogeneity of certain sediments. [6]

The high geochemical mobility of some of the NORM nuclides in the environment allows them to move easily and to contaminate much of the environment with which humans come in contact. [12]

2.4.2 Mosses

The overall release of the radioactive material from the Chernobyl accident was approximately 14×10^{18} Bq as of 26 April 1986, which included 85×10^{15} Bq of ^{137}Cs. A total of more than two hundred thousand square kilometre in Europe was contaminated with radioactive cesium (above 40×10^{3} Bq of ^{137}Cs per square metre) of which 71% was in the three most affected countries; Belarus, Russia and the Ukraine. [31]

Studies on the contamination of mosses by ^{137}Cs and ^{134}Cs from atmospheric nuclear weapon tests and/or the releases from the Chernobyl accident have been done over a number of years. Gazal and Prange [19] confirmed in their study that species of terrestrial mosses are particularly sensitive indicators of low levels of atmospheric radioactive caesium contamination and are good indicators of radioactive fallout, suggesting that terrestrial mosses may serve to elaborate a predictive modeling of caesium release.

Mosses are advantageous compared to some other species of bio-indicators as they have a large surface-to-mass ratio. Mishev et al. [18] observed that mosses have 10

times greater surface area compared to that of herbaceous grasses and their accumulating capacity is higher than in other plants. An example of a moss is shown in Figure 2.4.

Grodzinska et al. [7] mentioned several advantages that mosses have as indicator organisms:

1. The majority of these species are geographically widely distributed and occur plentifully in several natural habitats including industrial and urban areas;
2. They have no epidermis or cuticle, therefore metal ions can easily enter their cell walls;
3. They consist of no organs for the absorption of minerals from substrates, this is achieved mainly by precipitation;
4. Some species consist of a layered structure and yearly manufacture organic matter that makes discrete segments;
5. Transportation of minerals between segments is very poor because of lack of vascular tissues;
6. Mosses accumulate metals in a passive way, acting as ion exchangers, and
7. Mosses show the concentrations of most metals as a function of the amount of atmospheric deposition.

Figure 2.4 Moss specie *Pleurozium schreberi*

An atmospheric trace element usually accumulates in mosses, whether stable or unstable, natural or anthropogenic, which includes water-dissolved species from the environment. Several properties of the plant like morphology, metabolism, moss-carpet, as well as the elements concerned (e.g. electronic and nuclear properties, physical and chemical form), and the environmental circumstances and their inter-relations affect the accumulation of trace elements in mosses. [19]

Mosses release chemicals which elevate the acidity of water, stopping the process of decaying of dead organic material. Dead mosses do not decay because the anaerobic bacteria and fungi, which break down the material, cannot survive in oxygen-rich wet and acidic ground. This implies that the remains of mosses ultimately form the layer of soil known as peat.

This type of peat is often used to produce gardening manure to nurture plants as it lessens fungal infections. The formation of peat by the sphagnum mosses occurs very slowly, taking 10 to 100 years to produce a layer of 1 to 10 cm peat.[28]

2.5 Instrumentation

2.5.1 High purity germanium (HPGe) gamma ray spectrometry

A typical gamma-spectrometry system consists of a germanium (Ge) detector, a liquid nitrogen or mechanical cooling system, pre-amplifier, detector bias supply, linear amplifier, analogue-to-digital converter (ADC), multi-channel storage of the data and data readout devices. A typical detector/Dewar and electronic block diagram are shown in Figures 2.5 and 2.6.

The most discriminating factor of gamma ray (HPGe) spectrometry is the high resolution of the solid state detector it uses. An accurate full-energy-peak efficiency value as a function of energy can be established for a given counting geometry for individual HPGe detectors.

Hult et al. [4] noted that the major contributions to the background in gamma-ray spectrometry come from

(1) ambient radioactivity in the laboratory

(2) ^{222}Rn and its daughters

(3) radioactivity in the detector and the shield, and

(4) cosmogenically induced background.

The detector is shielded from environmental radioactivity and the laboratory (e.g. floors/walls) using high-Z materials (e.g. lead).

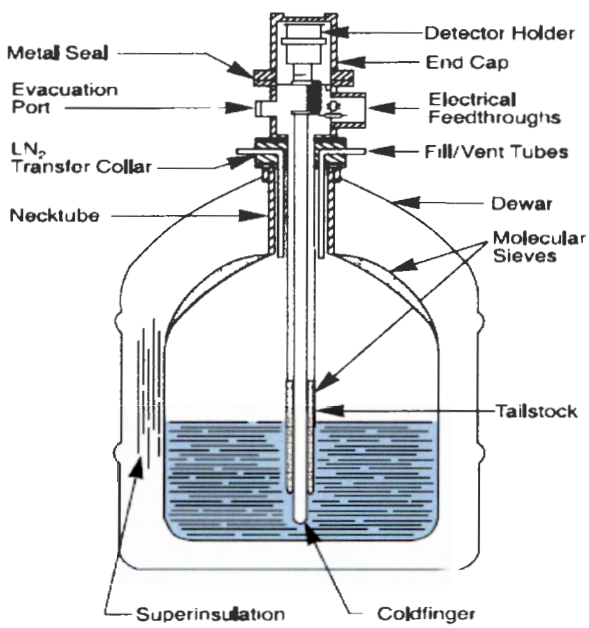

Figure 2.5 Vertical dipstick cryostat [37]

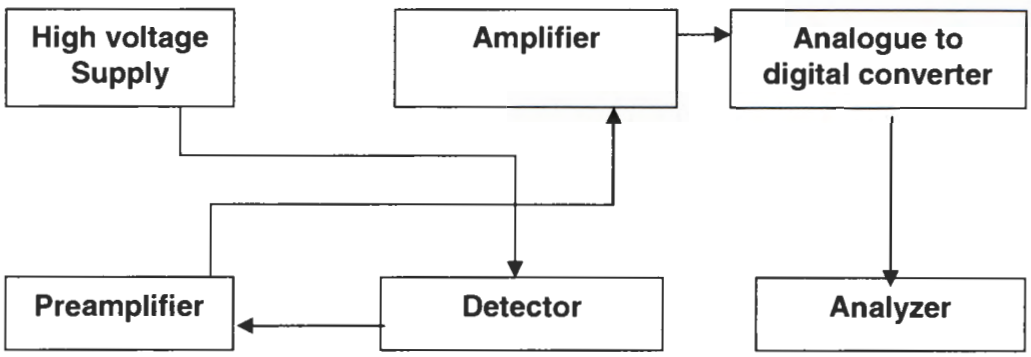

Figure 2.6 Block diagram of the gamma spectrometer

Germanium semiconductor detectors use the electronic carriers (electron-ion and electron-hole pairs) created by the absorption of gamma ray photons in the germanium, causing a flow of electric current through the semiconductor and produce an output voltage pulse of amplitude proportional to the energy of the incident gamma photon. The detector consists of a germanium crystal mounted in a vacuum cryostat cooled to temperatures as low as -196 °C (77 K). Cooling is done by the insertion of the cryostat in a dewar vessel filled with liquid nitrogen or alternatively electric cooling can be applied, which has been developed recently to allow operation of gamma spectrometry systems in remote areas where liquid nitrogen is not readily available.

Gamma ray spectrometry uses the direct proportionality between the energy of an incoming gamma ray and the pulse amplitude at the output of the detector. After amplification and digitisation, the pulse amplitudes are analysed, and the output of the spectrometer is an energy sorted spectrum of the detected radiation. Radionuclides individually emit specific gamma ray energies and accordingly the gamma ray spectra can be used to diagnose the source of the radiation.

Calibration standards of known nuclides and activity are used for energy and efficiency calibrations. The calibration samples should be as similar as possible to the field samples in every respect namely matrix composition, physical form and dimensions. It must be possible to put the field samples in the same position relative to the detector to avoid geometric differences and accordingly the efficiency calibration.

2.5.2 Gas-flow proportional alpha-beta counter

The major advantage of this method generally is the high detection efficiency, which may minimize the sample counting time to achieve a specific minimum detectable activity (MDA). The disadvantage is that it lacks the ability to discriminate between the energy of the particles needed and characterize alpha or beta particles according to their energies. Gross alpha-beta counting is therefore used as a screening technique to obtain an approximate total alpha and beta activity.

The main component of a gross alpha/beta counter consists of

(1) a detector,

(2) a bias voltage supply,

(3) an amplifier,

(4) a pulse selection or discriminator and

(5) scalers.

A sample changer and auxiliary equipment are additional components, which form part of the total gas-flow proportional counting system (Figure 2.7). A thin window is positioned between the sample and the detector to shield the detector from external contamination. The window is made from a thin Mylar foil (to make it strong) covered with a thin layer of aluminium (to make it electrically conductive). The thin wire anode is stretched crosswise inside the counting volume to improve the collection of electrical charge. [30] It is not possible to have an entrance window that is both very thin and vacuum tight and there is always a small amount of gas being lost from the detector. These small leaks can be overcome by connecting a supply of counting gas at a slight over-pressure to the detector, and to flush it continuously with this gas. Argon with 10 % methane as quenching agent (called "P10 gas") is the most popular counting gas used in this type of detectors. The gas handling systems are designed to have the detectors filled to a pressure that is 50 to 100 kPa above atmospheric value. The operation voltages of these detectors vary between 1500 and 2500 Volt depending on their construction and application. [30]

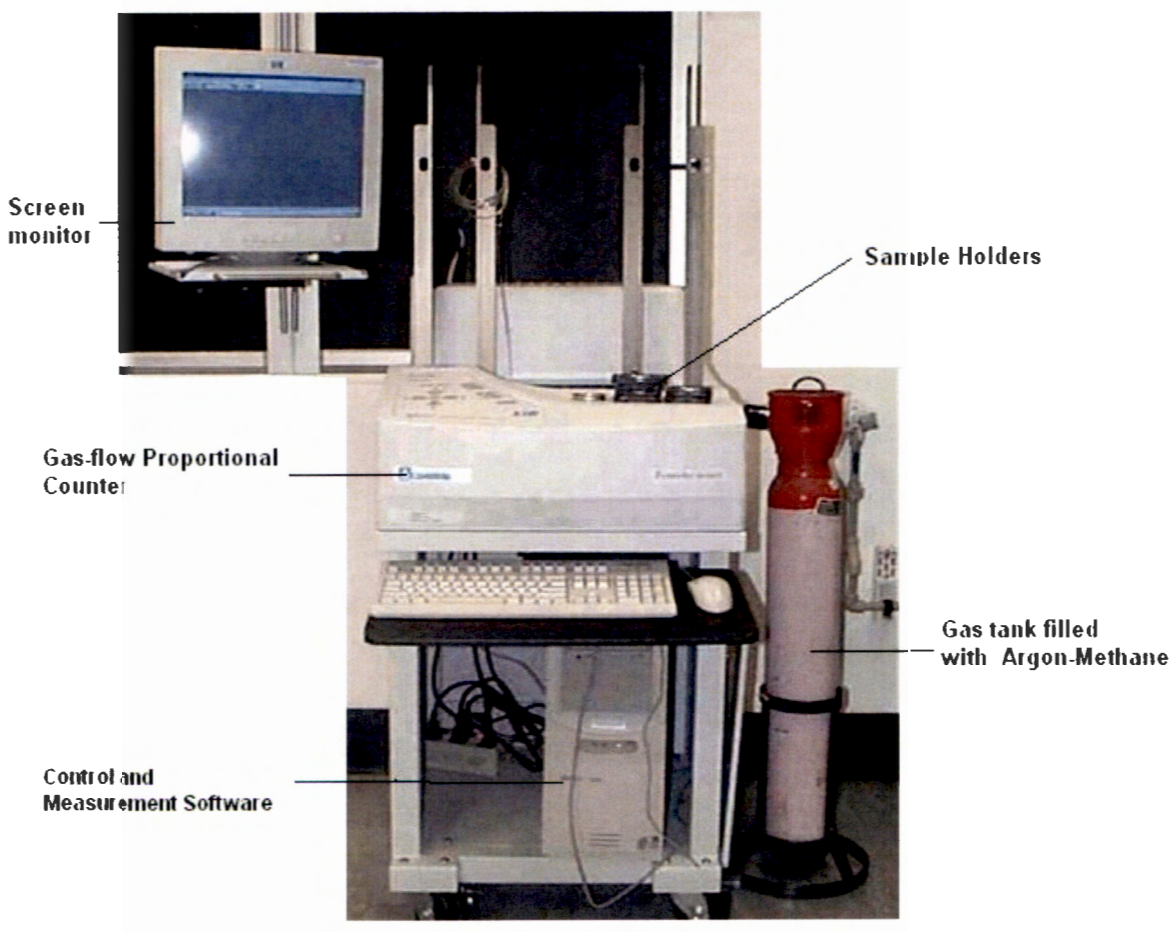

Figure 2.7 Gas-flow proportional counter

Measuring alpha and beta activity by the gas-flow proportional counter is done in two channels, which one can adjust to counting at the alpha plateau in which mode it discriminates the beta particle activity, whereas counting at the beta plateau one discriminates against the alpha particle activity present in the sample. Normally the two channels are set to collect particles of mainly alpha in the one and mainly beta in the other channel, which obviously will cause interference from alpha in the beta channel and vice versa, also called crosstalk. In practice the α-to-β channels crosstalk normally occurs around 10% while β-to-α channels should be <1%. [5]

The calibration efficiencies were carried out for gross beta counting using a ^{90}Sr (E_β = 0.546 MeV) standard solution, which is in equilibrium with ^{90}Y (E_β = 2.281 MeV), while for gross alpha counting a standard solution of ^{241}Am (E_α = 5.49 MeV). A measured volume of either alpha or beta standard solution was used to prepare sources of homogeneous solid or liquid matrix to depict the actual environmental sample.

The method to prepare calibration samples was based on a mineral with strong ion exchange properties to act both as adsorption medium for radioactive tracer and attenuation medium (for alpha- and beta-particles), and a binder (polyvinyl acrylate) to keep the dry powder in the standard together. Attenuation ranges were from 0 to 300 mg of residual mass in steps of 50 and 100 mg. This range can be expanded, or covered more or less closely by simple adjustment of the quantities of material used.

3. EXPERIMENTAL METHODS

3.1 Sampling

The study areas include the main catchment of the Wonderfonteinspruit identified for investigation of NORM and possibly fission related radionuclides in the sediments. The river was selected according to the type of land use activities surrounding the catchment area and the importance of the water quality and integrity of the water resources.

In Minsk, Belarus, mosses were sampled as part of a collaborative project between the Department of Science and Technology (DST) and the Joint Institute of Nuclear Research (JINR) in the Russian Federation. Some of the samples were sent to Necsa for gamma-spectrometric analysis of NORM and fission related radionuclides. Belarus was one of the former nuclear weapons testing sites in the Russian Federation and also influenced by the nuclear power plant accident (Chernobyl accident) caused elevated emission of radioactive nuclides into the atmosphere which re-settled into the environment.

3.1.1 Wonderfonteinspruit

The Wonderfonteinspruit catchment area is located to the south-west of Johannesburg, with the upper section of catchment in the Gauteng Province and the lower part in the North West Province (Figure 3.1). This catchment area includes the eastern part of the Mooi River. The catchment area is mostly underlain by dolomite whose compartments are dewatered by the gold mines. The study area of interest lies between Krugersdorp in the north-east and the inflow into the Mooi River north of Potchefstroom in the south-west. This study concerned the lower part of the Wonderfonteinspruit catchment area between the end of the pipeline from Carletonville to Potchefstroom.

The source of the Wonderfonteinspruit is in the Krugersdorp area and it flows through the Tudor Dam and the Attenuation Dam past Kagiso, Azaadville and Randfontein into the Donaldson Dam near Bekkersdal. It is then partitioned into a large (1 m diameter) pipeline at the Donaldson Dam, which transfers the water over the dolomitic groundwater compartments, dewatered due to gold mining activities, until a discharge point near Carletonville. From Carletonville, the river runs south-west passing Oberholzer, Khutsong, and Welverdiend assembling with the Mooi River near the Gerhardminnerbron and flowing together south into the Boskop Dam and further to Potchefstroom. Dams forming part of the catchment (i.e. between Carletonville and Potchefstroom) include Harry's Dam, the Padda Dam, the Coetzee Dam, and the Visser Dam, as well as the large Boskop and Potchefstroom Dams.

The sampling of sediments evaluated in this study on the Wonderfonteinspruit was done from Harry's dam (S26 19.038 E27 23.395) to Visser dam (S26 23.119 E27 12.785) which form part of this main catchment area. These sampling sites are found between Krugersdorp and Potchefstroom which are made up of the Harry's Dam, including Middle Vlei, Big Dam, Waterway, Coetzee Dam and Visser Dam at the first and second sections. Maps depicting the sampling points (i.e. field identities) along some tributaries are presented in Appendix 3.

The land surrounding these catchments is mainly used for mining, especially gold mines which result in drainage of acidic mine waters. (6)

Mining in the study area is spatially concentrated at two goldfields, namely the West Rand covering a large portion of the non-dolomite headwater region of the Wonderfonteinspruit catchments, with many dysfunctional and abandoned mining sites, and the Far West Rand in the upper part of the lower Wonderfonteinspruit, consisting of the 'West Wits Line' (mines around the town of Westonaria) and the 'Carltonville mining area' near the city of Merafong. (6)

The mine tailings dams, sand dumps, and rock dumps are potentially significant contributors to spread contamination. The dust, generally generated when surface soil, mine dumps, and surface materials at the site are suspended by wind or disturbed by site/mining activities, eventually ends up in the river basin. The principal mechanisms for the contamination of downstream sediments are the mechanical erosion of tailings, which has been observed in many of the rivers downstream of the mining areas, the precipitation of metal-rich minerals in the wetlands systems, or the bio-accumulation of metals in the wetland biota. (14)

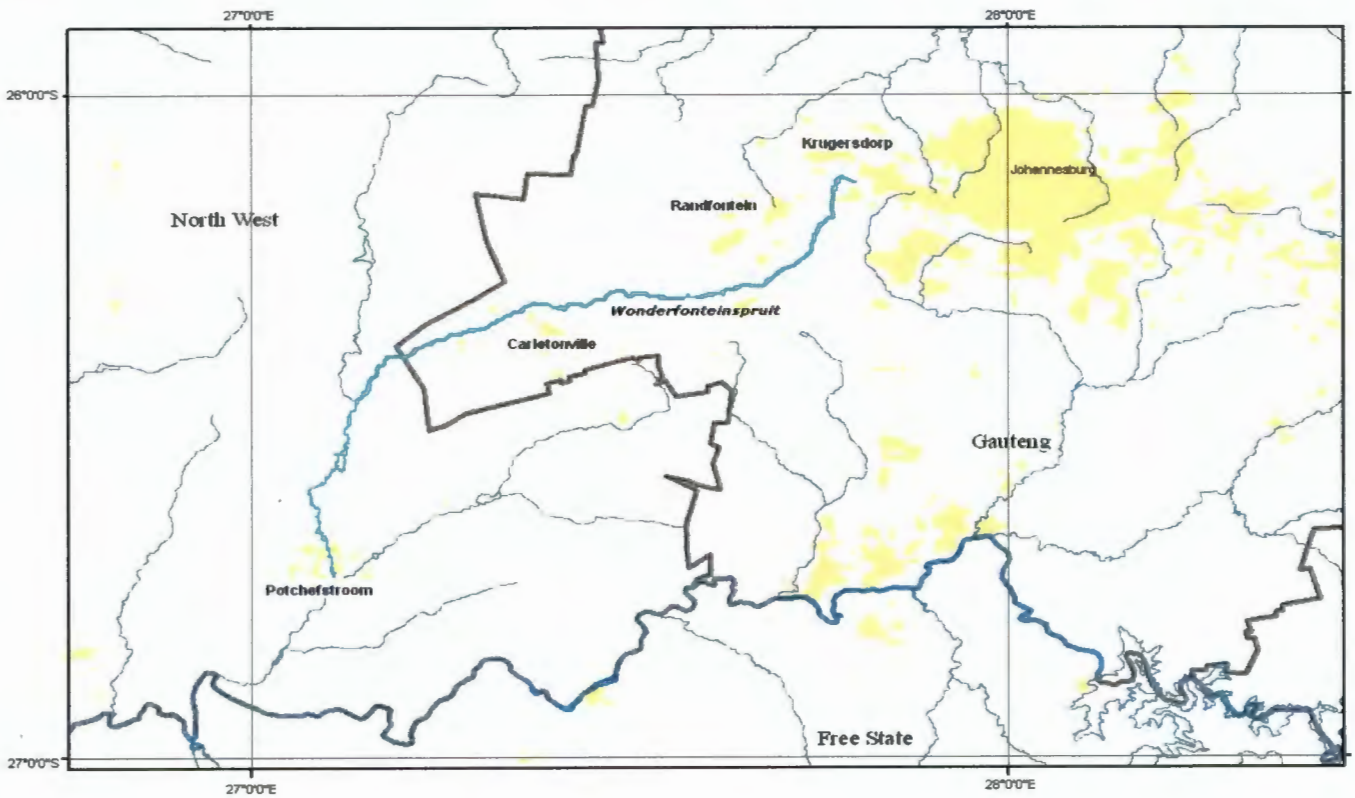

Figure 3.1 The Vaal river catchment areas with the Wonderfonteinspruit between Krugersdorp and Potchefstroom

Sediments may also become a source of short- or long-term contamination; bottom sediments can be disturbed by physical processes (e.g. erosion and re-suspension due to flood events, deposition after flooding, dredging) or by chemical and biological processes (interaction with overlying water, bioturbation). (10) The contaminants and

radionuclides stored in the sediments are not a direct threat to man in that state but may become available through transfer to biota and then further to man. [12]

Farming is not practised extensively in the area, but the farming activities that are encountered are temporary dry land and livestock. The development of settlements around the catchment also plays a role in the overall impact on the environment and the water quality. People living along the catchment may be using this contaminated water for drinking and agriculture, increasing the uptake of these radioactive nuclides. [14]

3.1.2 Minsk

The sampling of mosses was done in Minsk, Belarus, (Figure 3.2).

Belarus is a neighbouring country of Russia and Ukraine, where most of the emissions of radioactive nuclides occurred as result of the testing of nuclear weapons (underground, surface and atmospheric experiments) and the Chernobyl nuclear power plant accident. The dispersal of these radionuclides caused their accumulation in the environment of Belarus. Minsk, the capital city of Belarus, where some 100 moss samples were taken over an area of around 100 km^2 is almost in the centre of the country and the measurements on the mosses could reveal the distribution of these radioactive nuclides.

Figure 3.2 Belarus, Russia and Ukraine map [33]

Analysis of mosses for fallout products would indicate the impact the nuclear related activities had over the years on the environment. Forests in Belarus account for 36%

of the country's area and the flora includes 435 mosses species. The name of the type of moss plant sampled was pleurozium schereberi. These mosses are always moist, spongy (because of their wet surroundings) and range in colour from orange to greenand their cells are large enough to allow the movement of water in and out of pores.

3.2 Sampling Equipment and Methodology

3.2.1 The Wonderfonteinspruit catchment area

The equipment used, chosen during sampling on site, was based on the depth of water, the kind and the characteristic of the sediments (density, mixed with stones), the velocity of the stream water, and the convenience of the sampling sites. [16]

A "Shipek" grab sampler of about 50 kg mass was used for taking samples from sites with deeper depth, while a "mini-Shipek" of about 5 kg was used for sampling surface sediments. The equipment was able to sample soft, fine grained to sandy sediments from varying depths of the river system. This type of sampler can only be used where no rocks or hard material are present at a sampling site. Some samples were dark in colour, with heavy clay content and an amount of organic matter (Figure 3.3), while other sediment samples had a dark brown colour and contained less clay. Samples were placed in a thick transparent plastic bag at the sampling sites and taken to the laboratory for drying, grinding and pulverising to a homogeneous powder.

Figure 3.3 Sediment sample right after sampling (the long black "snake")

A systematic grid plan of sampling was made to allow sampling at approximately 1 km intervals along the stream. The sampling pattern at the site itself varied with respect to the type of sediments found. Finely grained sediments were taken 10 to 20 metres apart, while gravel or very coarse samples were ignored or else small amounts of finer material (about 4 mm) were taken. A grid was formed which a linear or square or even triangular had shaped pattern.

The total number of sediment samples taken from these tributaries in the Wonderfonteinspruit catchment area was about 248. In addition to these samples

another two samples from the Klerkskraal Dam were taken for background observations. The number of samples taken at various locations is shown in Table 3.1.

Table 3.1 Tributaries located in the Wonderfonteinspruit catchment area and the number of samples taken

Location	Coordinates	Number of samples
Harry's Dam	S26.19.038 E27.23.395 to S26.19.092 E27.23.344	56
Middle Vlei	S26.19.129 E27.23.255 to S26.19.133 E27.21.608	8
Big Dam	S26.19.991 E27.20.517 to S26 20.306 E27.19.870	47
Waterway	S26.20.451 E27.19.645 to S26 21.937 E27.15.989	21
Coetzee Dam	S26.22.160 E27.14.523 to S26.22.387 E27.14.285	70
Visser Dam 1	S26.22.613 E27.13.708 to S26.22.882 E27.13.490	25
Visser Dam 2	S26.22.902 E27.13.156 to S26.23.119 E27.12.785	20

3.2.2 The Minsk area

Samples were taken by a PhD-student from the Joint Institute of Nuclear Research (JINR), Dubna, Russian Federation. Some 100 samples were taken within a grid of approximately 100 km by 100 km. The mosses were collected from an area of approximately 1 m^2 and 10 cm in depth. The samples were dried and transported to the JINR where they were milled and pulverized. The mass of about 500 gram of 10 samples more or less representative of the grid were taken to Necsa for gamma-spectrometric measurements to verify the results obtained from other collaborating institutes that used less state of the art gamma spectrometric equipment.

3.3 Gamma Analysis

The samples were measured with broad energy gamma-ray spectrometric system, consisting of an n-type coaxial HPGe detector (Canberra BE5030) with 2 keV resolution at 1.33 MeV. The detector was mounted within a lead castle with inside dimensions of 40 cm x 40 cm x 40 cm (cubic shape). The lead castle is made of a 13 cm thick lead with less than 50 Bq/kg ^{210}Pb activity, lined inside with a layer of 2 cm lead with an activity of less than 10 Bq/kg. The lead castle is lined inside with 1 mm of cadmium, 2 mm of copper and 4 mm of Perspex to reduce x-ray formation. The lead castle itself is fitted with a Perspex "shield", which was shaped around the entire set-up to allow flushing with nitrogen to prevent radon from the environment to enter the cavity of the lead castle.

Samples (both sediments and mosses) were prepared using "lid-dish" containers of 70 mm diameter x 5 mm height pressed to uniform shape with a hydraulic press at 25 bar pressure.

Three main tasks had to be done in order to operate the counting system, they were:

1. Energy calibration, that is the relationship between the channel number and energy
2. Peak width calibration, that is the variation of peak width with energy, and
3. Efficiency calibration, which is relationship between number of counts and the disintegration rate with energy.

The energy calibration is a function that correlates each channel in the displayed spectrum with a specific energy. It enables peaks observed in the calibrated spectrum to be identified according to their energy.

The calibration of the efficiency was determined using actual samples. A certified ^{152}Eu sample was used to spike a sediment sample resulting in 0.375 ± 0.0047 kBq/g and a moss sample separately to obtain sample activity of 0.6376 ± 0.008 kBq/g. The spiked samples were counted for 1 hour and the spectra obtained were used to determine the efficiency calibration curve. As ^{152}Eu has a wide variety of gamma energies up to 1500 keV these samples were also adequate to determine the peak-width variation with energy. Efficiency calibration equations resulted from counting spiked sediment and moss sources respectively were as follows:

$$\ln(Efficiency) = -25.21 + 16.94 \cdot \ln(E) - 4.335 \cdot \ln(E)^2 + 0.469 \cdot \ln(E)^3 - 0.019 \cdot \ln(E)^4 \quad (1)$$

and,

$$\ln(Efficiency) = -31.62 + 23.07 \cdot \ln(E) - 6.33 \cdot \ln(E)^2 + 0.741 \cdot \ln(E)^3 - 0.032 \cdot \ln(E)^4 \quad (2)$$

Data acquisition was controlled with gamma-ray spectrometric software Genie-2000 [35] installed on a standard desktop PC. The software package was used for evaluation of the gamma spectra and calculation of the activity concentrations.

3.4 Gross alpha-beta measurements

A compressed sample with a 25 mm diameter and 5 mm height was prepared, with a typical mass in the range of 0.25 g to 1.0 g depending on the specific density of the material concemed. ^{241}Am (413.4 ± 4.10 Bq/g) and ^{90}Sr/^{90}Y (472.2 ± 7.10 Bq/g) were used as alpha and beta sources respectively to calibrate the efficiency for alpha and beta activity respectively. Calibration samples were prepared in $CaSO_4$ equivalent matrices to determine the self-absorption in relation to sample thickness and density.

3.5 Sample Activity Determination

3.5.1 Gamma Counting

Most of the sediment samples were counted for 1 hour (Number of samples, n = 235), some from 10 hours (n = 2), 12 hours (n = 1), only one for 14 hours overnight and a few on weekends for 15 hours (n = 9), depending on the availability of the counting equipment. One moss sample was counted for 10 hours and the other samples were counted for 1 hour each. Factors such as the distance between the source and the detector, physical dimensions of source and detector, intrinsic properties of the detector and the number of particles emitted for each atom decayed affect the counting efficiency of a measuring device.

The activity per unit mass of the sample, A, on the sampling date (decay corrected) for each energy line in the library matched with a line in the spectrum was calculated by the Genie-2000 software as follows: [35]

$$A = \frac{C}{M \cdot \varepsilon' \cdot y \cdot T_l \cdot K_c \cdot K_w} \quad (3)$$

where C is the net peak area,
M is the sample mass (g),
y is the branching ratio of the peak energy,
T_l is the live time of the measurement in seconds,
K_c is the correction factor for the nuclide decay during counting
K_w is the correction factor for the nuclide decay from the time the sample was collected till the start of the counting period,
ε' is the attenuation corrected efficiency, according to equation (4)

$$\varepsilon' = \varepsilon \cdot e^{-\mu(E)\rho t} \quad (4)$$

where ε is the non-attenuation corrected detection efficiency at the peak energy in question (if the attenuation correction has not been performed ε'=ε),
μ(E) is the mass attenuation (units of cm^2/g) at gamma energy E,
ρt is the average sample mass per unit area.

The correction factor for nuclide decay during counting, K_c, is expressed as follows:

$$K_C = \frac{T_{1_2}}{\ln(2) \cdot t_C}\left[1 - e^{-\frac{\ln(2) \cdot t_C}{T_{1_2}}}\right] \quad (5)$$

where $T_{½}$ is the half-life of the nuclide in question,
t_c is the elapsed real clock time during the measurement (in the same time units as $T_{½}$)

For all practical reasons, due to the long half-lives of the NORM series nuclides this correction factor will be unity (= 1).

According to equation (6), K_w, the correction factor for nuclide decay from the time the sample was collected till the start of the counting period is given by:

$$K_w = e^{-\frac{\ln(2) t_w}{T_{1_2}}} \quad (6)$$

where t_w is the elapsed clock time from the time the sample was taken to the beginning of the measurement (in the units as $T_{½}$).

Also here due to the long half-lives of the NORM series nuclides this correction factor can be regarded to be unity (= 1).

The random uncertainty in the activity, A, is calculated as

$$\sigma_A = A \cdot \sqrt{\left(\frac{\sigma_R}{100}\right)^2 + \left(\frac{\sigma_C}{C}\right)^2 + \left(\frac{\sigma_M}{M}\right)^2 + \left(\frac{\sigma_{\varepsilon'}}{\varepsilon'}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2 + \left(\frac{\sigma_K}{K}\right)^2} \qquad (7)$$

where σ_R is the relative error in the calibration due to the uncertainty of the reference source's activity
σ_C is the uncertainty of the net peak area C,
σ_M is the uncertainty of the sample quantity M,
σ_y is the uncertainty of the branching ratio y, and
σ_K is the uncertainty of the composite decay correction factor K,
$\sigma_{\varepsilon'}$ is the uncertainty of the effective efficiency, which is defined in equation (8)

$$\sigma_{\varepsilon'} = \varepsilon' \cdot \sqrt{\left(\sigma_{\varepsilon}/\varepsilon\right)^2 + \left(\rho t \cdot \sigma_{\mu(E)}\right)^2 + \left(\mu(E) \cdot \sigma_{\rho t}\right)^2} \qquad (8)$$

where ε is the non-attenuation corrected detection efficiency at the peak energy in question,
σ_ε is the uncertainty non-attenuated corrected detection efficiency,
$\mu(E)$ is the mass attenuation c (in units of cm^2/g) at gamma energy E,
ρt is the average sample mass per unit area,
$\sigma_{\mu(E)}$ is the uncertainty in $\mu(E)$, and
$\sigma_{\rho t}$ is the uncertainty in ρt.

The uncertainty of the composite decay correction factor, K, for buildup type "none" is defined as

$$\sigma_k = K \cdot \sqrt{\left(\frac{\sigma_{k_C}}{K_C}\right)^2 + \left(\frac{\sigma_{k_C}}{K_W}\right)^2} \qquad (9)$$

where K the composite decay correction factor itself is defined as, $K = K_C \cdot K_W$

The minimum detectable activity (MDA) is defined by;

$$MDA = \frac{L_D}{T_l \cdot \varepsilon' \cdot y \cdot M \cdot K_c \cdot K_w} \qquad (10)$$

which simpliflies similar to equation (1) where the net peak area (C) is substituted by L_D defined by:

L_D detection limit; defined as $L_D = 2.71 + 4.65 * B^{1/2}$, where B is the background value obtained for the same measuring period.

3.5.2 Gross alpha-beta counting

Each sediment sample was counted for 1 hour. The moss samples were counted for 5 hours each.

The basic relation between activity and pulses observed in the counting system is as follows: (30)

$$N = R \cdot t = A \cdot Y \cdot \varepsilon \cdot t \tag{11}$$

therefore including the mass equation (11) becomes equation (12) for activity;

$$A = \frac{N}{Y \cdot \varepsilon \cdot m \cdot t} \tag{12}$$

where
- A activity of the sample (Bq/g),
- N total number of counts observed in the counting period,
- Y the yield of the type of radiation that is measured,
- ε counting efficiency of the detector system for the type of particle,
- m mass of the sample (g),
- t counting period (s), and
- R observed count rate for the sample or background.

The activity concentrations of alpha (A_α) and beta (A_β) particles are calculated from the following equations: (34)

$$A_\alpha = \frac{N_A - B_A - X_\beta * \left(N_B - B_B\right)}{m * t * \varepsilon_\alpha * \left(1 - X_\alpha X_\beta\right)} \tag{13}$$

$$A_\beta = \frac{N_B - B_B - X_\alpha * \left(N_A - B_A\right)}{m * t * \varepsilon_\beta * \left(1 - X_\alpha X_\beta\right)} \tag{14}$$

with the uncertainty defined as,

$$\sigma(A_\alpha) = A_\alpha \cdot \frac{\sqrt{N_A + B_A + X_\beta^2 * (N_B + B_B)}}{N_A - B_A - X_\beta * (N_B - B_B)} \tag{15}$$

and

$$\sigma(A_\beta) = A_\beta \cdot \frac{\sqrt{N_B + B_B + X^2{}_\alpha * (N_A + B_A)}}{N_B - B_B - X_\alpha * (N_A - B_A)} \tag{16}$$

The detection limit for both alpha and beta activity in counts/second can be given as;

$$DL_\alpha = \frac{2.71 + 4.65 \cdot \sqrt{B_A + X_\beta * (N_\beta - B_B)}}{t} \tag{17}$$

and

$$DL_\beta = \frac{2.71 + 4.65 \cdot \sqrt{B_B + X_\alpha * (N_A - B_A)}}{t} \quad (18)$$

The minimum detectable activity (MDA) in Bq/g is then given by:

$$MDA_\alpha = \frac{DL_\alpha}{\varepsilon_\alpha \cdot m} \quad (19)$$

and

$$MDA_\beta = \frac{DL_\beta}{\varepsilon_\beta \cdot m} \quad (20)$$

where	A_α and A_β	the specific α- and β-activities (Bq/g) of the sample,
	N_α and N_β	the number of counts in the A- and B-channel of the detector,
	B_α and B_β	the number of background-readings in the two channels,
	ε_α and ε_β	the α- and β-efficiencies of the detector,
	X_α and X_β	the α- and β-cross talk (spill-over),
	DL_α and DL_β	the α- and β-detection limits,
	m	the mass of the sample (g), and
	t	the counting time (s) of the sample.

4. RESULTS AND DISCUSSION

The results obtained in this study are presented against the legislation related to the natural radioactivity exemption level.

4.1 Legislation

The results were evaluated against the bill of exclusion published in the Government Gazette of 28 April 2006, which states that in terms of the provision of section 2 (2) (b) of the Act, the Act does not apply where;

1. the level of radioactivity concentration of each radioactive nuclide in materials is below
   (a) 0.2 Bq per gram for artificial radioactive nuclides;
   (b) 0.5 Bq per gram for naturally occurring radioactive nuclides of uranium and thorium and their progeny except for radon;
   (c) 10 Bq per gram for potassium-40 in materials that are used in building construction or disposed of;
   (d) 50 Bq per gram for potassium-40 in all other materials *; or
2. the level of total radioactivity content is below 1000 Bq.

* *This is a flaw in the legislation as the maximum ^{40}K activity in pure potassium metal is 33 Bq and there will be no apparent reason that one would try to make ^{40}K-enriched potassium.*

4.2 Gamma spectra analysis results

The natural radionuclides, which this study concentrated upon, were the long-lived gamma-ray emitting nuclei from the decay series of ^{232}Th, ^{235}U, ^{238}U, as well as ^{40}K. The (man-made) fallout product ^{137}Cs was added to see if this nuclide was collected in the sediments in Southern Africa. The longer lived nuclides ($T_{1/2}$ > 1 year) in the decay series of ^{238}U, ^{235}U and ^{232}Th were assumed to be in secular equilibrium with their shorter-lived daughters ($T_{1/2}$ < 1 year) at the time of the sampling and measurements.

The radionuclides more generally detected from the measurements are given in Table 4.1, while those nuclides with interfering gamma energies are given in Table 4.2. Those nuclides that needed corrections will generally show higher uncertainties.

The following comments on the results obtained for the respective nuclides apply:

a. ^{238}U was not detected in most samples due to the low yield of its suitable gamma-line of about 0.06%. Normally its daughter nuclide ^{234}Th at 63.3 keV (4.8%) was used to determine the concentrations.

b. ^{226}Ra was determined by measuring its daughter nuclides, ^{214}Pb (295.21 keV) and ^{214}Bi (609.31 keV). The concentrations were also verified for possible radon loss on the 186 keV line of ^{226}Ra after correction for interference from ^{235}U, where possible.

c. ^{234}U corrected for interference of ^{214}Pb gave results with large uncertainties and as such provided little information. In the evaluation, ^{234}U was assumed to be in secular equilibrium with ^{238}U, which is a fair assumption regarding its origin as a result of mineral processing.

d. ^{230}Th was also normally not detected due to its low yield of 0.38%. In the final evaluation ^{230}Th was assumed to be negligible due to the fact that thorium is known to have a low mobility. [6]

e. ^{210}Pb at 46.5 keV was often detected in the sediment samples and its relatively long lived daughter ^{210}Po (138 days half-life), which has no suitable gamma-line, was assumed to be in secular equilibrium with ^{210}Pb, which is a fair assumption regarding the "age" of the sediments.

f. ^{235}U was determined on the 186 keV line after corrections for possible contributions from ^{226}Ra.

g. ^{231}Pa has no suitable gamma line and was assumed to be in equilibrium with its direct daughter ^{227}Ac, which may be still fair regarding the half-life of ^{227}Ac of 21 years and the "age" of the sediments.

h. ^{227}Ac (half-life 21 yr) was determined by its daughter ^{223}Ra, with verification of the results on ^{227}Th data, where possible.

i. ^{232}Th has no suitable gamma-line and accordingly could not be detected. Based again on the immobility assumption of thorium, the ^{232}Th concentration was regarded negligible in the final data evaluation.

j. ^{228}Ra was determined through its short-lived daughter ^{228}Ac.

k. ^{228}Th was determined through its short-lived daughters ^{212}Pb and ^{212}Bi.

l. ^{40}K and fallout product ^{137}Cs were measured directly using the 1460.81 keV and 661.66 keV gamma-lines, respectively.

Table 4.1 Measured radionuclides and their properties

Parent nuclide	Nuclide and Half-life	Mode of decay	Energy in keV	Yield in %
	^{238}U (4.5×10^{9} a)	Alpha	49.55	0.064
^{238}U	^{234}Th (24.1 d)	Beta	63.29	4.8
	^{234m}Pa (1.18 m)	Beta	1001.03	0.89
^{234}U	^{234}U (2.4×10^{5} a)	Alpha	53.2	0.12
^{230}Th	^{230}Th (7.52×10^{4} a)	Alpha	67.67	0.38
	^{226}Ra (1600 a)	Alpha	186.2	3.59
^{226}Ra	^{214}Pb (26 m)	Alpha	295.21	19.2
	^{214}Bi (19 m)	Beta	609.31	46.13
^{210}Pb	^{210}Pb (~22 a)	Beta	46.5	4
^{235}U	^{235}U (7×10^{5} a)	Alpha	143.8; 185.7	10.5; 54
	^{231}Th (24.64 h)	Beta	89.95; 81.228	0.94; 0.89
^{231}Pa	^{231}Pa (3.276×10^{4} a)	Beta	302.65	2.2
^{227}Ac (21.77 a)	^{227}Th (18.17 d)	Alpha	50.13	8
	^{223}Ra (11 d)	Alpha	338.28	2.79
^{228}Ra (5.75 a)	^{228}Ac (6.15 h)	Beta	911.21	26.6
^{228Th} (1.913 a)	^{212}Pb (10.64 h)	Beta	238.63	44.6
	^{212}Bi (60.55 m)	Beta	727.27	11.8
^{40}K	^{40}K (1.248×10^{9} a)	Beta	1460.81	10.67
^{137}Cs	^{137}Cs (30 a)	Beta	661.66	85.1
^{134}Cs	^{134}Cs (2.065 a)	Beta	795.86	85.5

4.3 Nuclide interference corrections

Corrections of overlapping gamma energy lines had to be done to account for the interference of nuclides of interest from others. Examples are given in Table 4.2 below.

Table 4.2 Isotopes measured, which need corrections from interfering gamma energy lines

Isotopes	Energy in keV	Yield (%)
^{238}U	49.55	0.064
^{227}Th	50.2	8.5
^{234}U	53.2	0.12
^{214}Pb	53.227	1.2
^{235}U	143.8	10.5
^{223}Ra	144.23	3.22
^{226}Ra	186	3.5
^{235}U	185.7	54
^{210}Pb	46.5	4.8
^{231}Pa	46.35	0.223
^{223}Ra	338.28	2.79
^{228}Ac	338.32	11.27
^{212}Bi	727.27	11.8
^{228}Ac	726.863	0.62

The general formula to calculate the activity from a specific gamma-peak is given by,

$$A = \frac{C}{I \cdot \varepsilon \cdot m \cdot t_m} \qquad (21)$$

where A is activity of measured isotope (Bq/g),
C is total number of counts (c),
I is the intensity (emission probability) of the peak,
ε is the counting efficiency of the peak at the specific energy,
m is the mass of the sample (g); and
t_m is the time of the measurement (s).

If we have one or more nuclides contributing to the same peak-area the total number of counts (C_T) can be written as,

$$C_T = \Sigma C_n \qquad (22)$$

where C_n is the contribution of each of n nuclides to the total counts

For the case of only one interfering nuclide at energy x, equation (22) can be written as,

$$C_T^x = C_1^x + C_2^x \qquad (23)$$

where, C_T^x = Total counts in the peak at energy of x keV
C_1^x = Counts of the nuclide of interest in the peak at energy of x keV
C_2^x = Counts of the interfering nuclide in the peak at energy of x keV

Solving for C_1 as the nuclide of interest, equation (23) rewrites to,

$$C_1^x = C_T^x - C_2^x \qquad (24)$$

If the interfering nuclide also has a peak at an energy of y keV, which is interference free, one also knows the activity of the interfering nuclide at the energy of x keV, or

$$A_2^x = A_2^y \qquad (25)$$

Expressed in counts one arrives at,

$$\frac{C_2^x}{I_2^x \cdot \varepsilon_2^x \cdot m \cdot t_m} = A_2^y \qquad (26)$$

Substitution of equation (26) in (24) leads to,

$$C_1^x = C_T^x - A_2^y (I_2^x . \varepsilon_2^x . m . t_m) \qquad (27)$$

Expressed in activity one arrives at,

$$A_1^x = A_T^x - A_2^y (I_2^x . \varepsilon_2^x . m . t_m).(I_1^x . \varepsilon_1^x . m . t_m)^{-1} \qquad (28)$$

As $\varepsilon_2^x = \varepsilon_1^x$ (same energy x, different nuclides) (29)

Equation (28) can be reduced to

$$A_1^x = A_T^x - A_2^y(I_2^x).(I_1^x)^{-1} \quad (30)$$

where A_T^x = Uncorrected activity reported for the nuclide of interest at the energy of x keV

Corrections for more than one interference then lead to additional corrections in equation (30), which can be expressed by,

$$A_1^x = A_T^x - A_2^y(I_2^x).(I_1^x)^{-1} - \ldots\ldots\ldots - A_n^z(I_n^z).(I_1^x)^{-1} \quad (31)$$

Since the uncertainty in A_T^x , represented by $\sigma_{A_T^x}$ and the uncertainty in A_n^z by $\sigma_{A_n^z}$, the uncertainty in A_1^x is given by,

$$\sigma_{A_1^x} = \sqrt{(\sigma_{A_T^x})^2 + ((\sigma_{A_2^y}/A_2^y)\cdot(I_2^x)\cdot(I_1^x)^{-1})^2 + \ldots\ldots\ldots\ldots + ((\sigma_{A_n^z}/A_n^z)\cdot(I_n^z)\cdot(I_1^x)^{-1})^2} \quad (32)$$

4.4 Nuclide distribution in sediments along the Wonderfonteinspruit catchment area

The activities measured for the ^{232}Th decay chain in sediment samples were previously observed to be low and close to natural background levels in the catchment area, while elevated levels of uranium were found. [9] In general, the activity concentration levels of sediments are dominated by the ^{238}U decay chain nuclides, exhibiting distinct spatial variations in activity levels and ratios depending on radionuclide source terms and relevant transport processes and environmental conditions. The nuclide specific results are given in Appendix 1. From this we can evaluate the distribution of the individual nuclides within the three series, both in terms of absolute concentration as well as relative concentration between members of the same chain. Graphs were plotted to illustrate the concentrations of various nuclides measured in the Wonderfonteinspruit catchment area.

4.4.1 ^{238}U-chain

The average ^{238}U activity, determined from the daughter ^{234}Th, was 0.934 ± 0.014 Bq/g (median 0.621), which is almost twice the legislative exemption level for natural radioactive materials of 0.5 Bq/g (paragraph 4.1). The maximum concentration was observed at the Coetzee Dam (S26 22.170 E27 14.492; D7.020) of about 7.4 ± 1.1 Bq/g. The graphical representation of the concentration distribution along the catchment area is shown in Figure 4.1.

The ^{226}Ra activity concentrations determined through its daughter nuclides, ^{214}Pb and ^{214}Bi, averaged 0.260 ± 0.004 Bq/g (median 0.182) along the catchment area with the highest activity observed at Harry's Dam (S26 19.039 E27 23.302; A1.17.B) of about 1.23 ± 0.02 Bq/g. The graphical representation of the concentration distribution along the catchment area is shown in Figure 4.2.

The ^{210}Pb average activity was about 0.27 ± 0.02 Bq/g, with the highest concentration observed at the Coetzee Dam (S26 22.170 E27 14.492; D7.020) of 1.67 ± 0.11 Bq/g.

The graphical representation of the concentration distribution along the catchment area is shown in Figure 4.3.

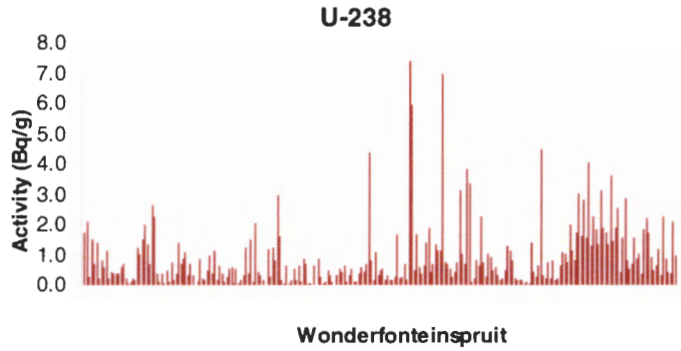

Figure 4.1 Concentration levels of ^{238}U in the WCA

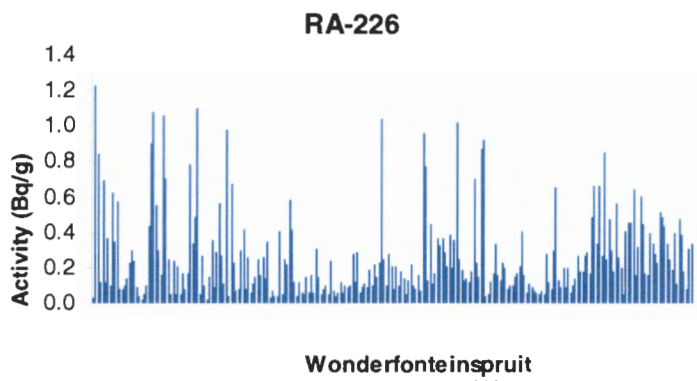

Figure 4.2 Concentration levels of ^{226}Ra in the WCA

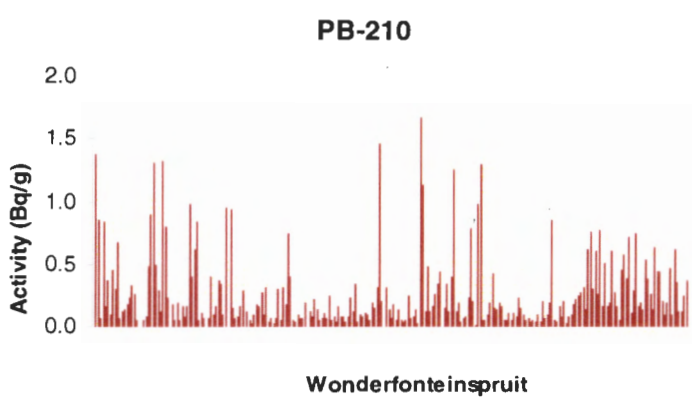

Figure 4.3 ^{210}Pb concentration plot of the WCA

From Figures 4.1, 4.2, and 4.3 it seems that there is a good correlation between ^{210}Pb and ^{226}Ra and some correlation between ^{226}Ra and ^{238}U.
The database from (Appendix 1) the following correlations for the $^{226}Ra/^{238}U$-ratio and $^{210}Pb/^{226}Ra$-ratio through linear regression are obtained:

Average $^{238}U/^{226}Ra$-ratio = 3.564 ± 0.006 (Median = 3.187)

$[^{238}U] = (3.439 \pm 0.127) . [^{226}Ra]$; $R^2 = 0.57$

and,

Average $^{226}Ra/^{210}Pb$-ratio = 1.176 ± 0.012 (Median = 1.040)

$[^{226}Ra] = (1.083 \pm 0.017) . [^{210}Pb]$; $R^2 = 0.90$

Graphical representation of ^{238}U-^{226}Ra and ^{226}Ra-^{210}Pb correlations are shown in Figures 4.4 and 4.5, respectively.

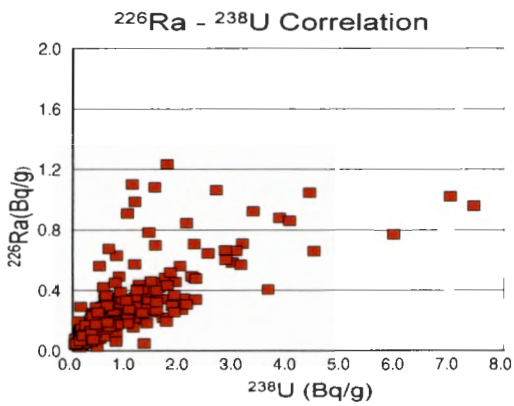

Figure 4.4 ^{238}U - ^{226}Ra correlation

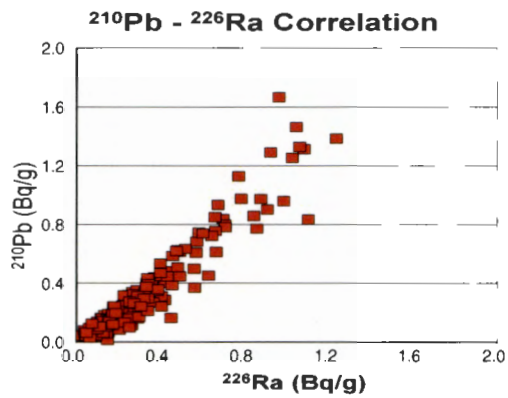

Figure 4.5 ^{226}Ra - ^{210}Pb correlation

From this it can be concluded that the concentrations of ^{238}U and ^{226}Ra seem to be related to a certain extent, but that at numerous points the ^{226}Ra concentration is relatively increased. If ^{226}Ra would originate due to ingrowth from only ^{238}U deposited in the sediments, the average and median $^{238}U/^{226}Ra$ ratios would suggest that the ^{238}U deposition would have happened some 800 years ago, which is obviously not the case. From Figure 4.4 it is observed that there seems to be an 8-fold higher ^{238}U activity compared to ^{226}Ra and that at lower concentrations there are numerous points where the two nuclides have similar activities, which may have been caused by direct run-off from the tailing dams where the two nuclides can be assumed to be in equilibrium. Furthermore, from the database two samples (one in Harry's Dam and one in the Waterway) can be identified where the ^{226}Ra activity is about twice the ^{238}U avctivity, which may be due to run-off of phosphate fertilizers, which are known to contain elevated radium (^{226}Ra and ^{228}Ra) levels. Accordingly, it is concluded that uranium and radium are released from mining and mineral processing activities through pumping of underground water which contains these two nuclides at different concentrations and that these two nuclides have different mobilities in the catchment area, which at certain points is aggrevated by direct contamination from mine tailings either through direct run-off or wind-blown dust deposition.

On the other hand, it seems that the concentrations of ^{226}Ra and ^{210}Pb are directly related. If ^{210}Pb would originate due to ingrowth from the ^{226}Ra deposited in the sediments, the average and median $^{226}Ra/^{210}Pb$ ratios would suggest that the ^{226}Ra deposition on average would have happened some 75 years ago, which is a quite feasible option (1-meter sediment samples represent about 50 years of

sedimentation) indicating an almost insignificant deposition of ^{210}Pb through underground water pumping but also that the mobility of ^{226}Ra once adsorbed to the sediments, is low in the catchment area.

4.4.2 ^{235}U-chain

The average ^{235}U activity, determined from the nuclide itself corrected for the contribution of ^{226}Ra, was 0.040 ± 0.004 Bq/g (median 0.0156), which is well within the legislative exemption level for natural radioactive materials of 0.5 Bq/g (paragraph 4.1). The maximum concentration of about 0.341 ± 0.045 Bq/g (which, as should be, coincides with the highest ^{238}U concentration) was observed at the Coetzee Dam (S26 22.170 E27 14.492; D7.020). The graphical representation of the concentration distribution along the catchment area is shown in Figure 4.6. It should be noted that the negative values are due to over-correction from ^{226}Ra, meaning there is more ^{226}Ra than ^{235}U.

The ^{227}Ac activity concentrations determined through its daughter nuclides, ^{227}Th and ^{223}Ra, averaged at 0.107 ± 0.010 Bq/g (median 0.036) along the catchment area with the highest activity value of 0.923 ± 0.110 Bq/g was observed at the Visser-1 Dam (S26 22.814 E27 13.446; H2.A). However, it should be noted that the six highest concentrations out of 50 values obtained, were from the Visser-1 Dam. The graphical representation of the concentration distribution along the catchment area is shown in Figure 4.7.

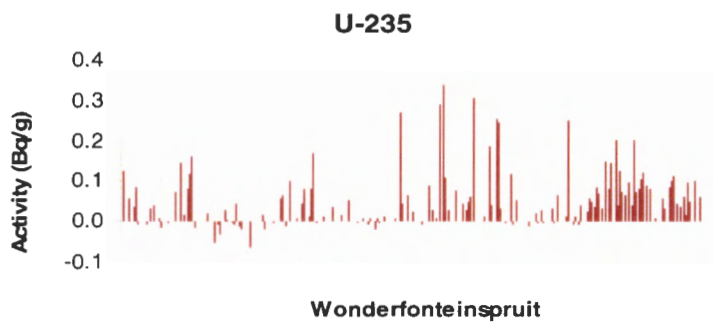

Figure 4.6 ^{235}U concentration plot of the WCA

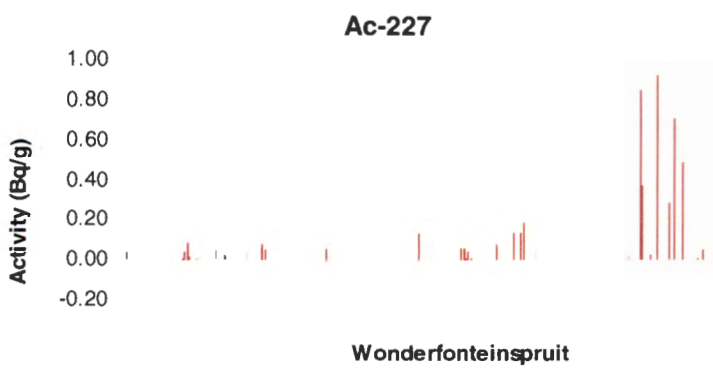

Figure 4.7 ^{227}Ac concentration plot of the WCA

From Figures 4.8 and 4.9 it seems that there is a fair correlation between ^{235}U and ^{238}U regarding the statistics at the lower concentrations especially for ^{235}U, but basically no correlation between ^{227}Ac and ^{235}U. From the data (Appendix 1) the following correlations for the ^{235}U-^{238}U activity and the ^{227}Ac-^{235}U activity through linear regression were obtained:

$$[^{235}U] = (0.0461 \pm 0.0012) \cdot [^{238}U], \qquad R^2 = 0.82$$

and,

$$[^{227}Ac] = (0.203 \pm 0.069) \cdot [^{235}U], \qquad R^2 = -0.36$$

It should be noted that in natural ore the activity ratio between ^{235}U and ^{238}U is about 0.048, which compares well with the value obtained through linear regression.

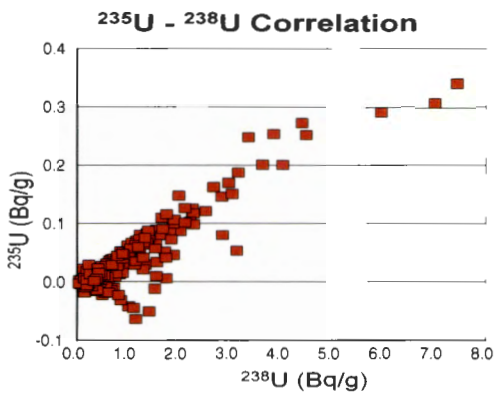

Figure 4.8 ^{235}U – ^{238}U correlation

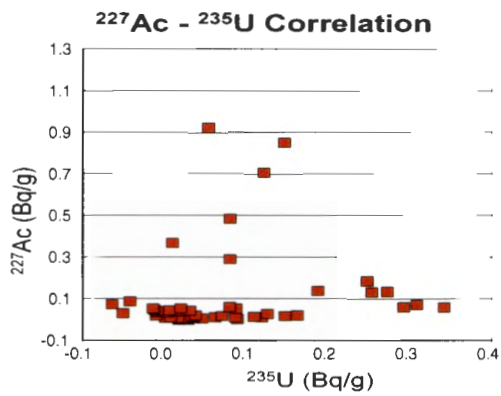

Figure 4.9 ^{227}Ac – ^{235}U correlation

From this it can be concluded that the concentrations of ^{238}U and ^{235}U are related as expected in the natural environment. Furthermore, it seems that ^{227}Ac is more or less evenly distributed throughout the catchment area except for some six samples with elevated concentrations, all six located in the Visser 1 dam. Excluding these points, the average ^{227}Ac concentration over the catchment area is 0.039 ± 0.003 Bq/g. This indicates a natural background in the catchment area of 65 ± 5 ppm uranium. Regarding the age of the sediments compared to the half-life of ^{227}Ac (22 years), it should be concluded that the long-lived parent ^{231}Pa but not detected is also present and in equilibrium with ^{227}Ac. The cause of the elevated ^{227}Ac levels in the Visser 1 Dam is not clear and needs further investigation whether this is due to specific waste entering the catchment area between the Coetzee and Visser-1 dams, especially as both ^{227}Ac and ^{231}Pa have of the highest dose conversion factors of all the nuclides in the three natural decay series.

4.4.3 ^{232}Th-chain

The ^{232}Th-chain has relatively short-lived progeny compared to the age of the sediments. ^{228}Ra with a half-life of 5.75 years is determined by the activity of its short-lived daughter ^{228}Ac (6.13 hours), while ^{228}Th (1.91 year) is determined from its daughters ^{212}Pb and ^{212}Bi.

The average ^{228}Ra activity was 45.4 ± 0.9 mBq/g (median 39.5), which is far below the legislative exemption level for natural radioactive materials of 0.5 Bq/g (paragraph 4.1). The maximum concentration was observed in the Visser Dam 2 (S26 23.016 E27 12.924; E3.A) of about 154 ± 64 mBq/g. The graphical representation of the concentration distribution along the catchment area is shown in Figure 4.10.

The average ^{228}Th activity was 75.5 ± 0.4 mBq/g (median 71.0), with the highest concentration observed at Harry's Dam (S26 19.062 E27 23.336) of 217 ± 11 mBq/g. The graphical representation of the concentration distribution along the catchment area is shown in Figure 4.11.

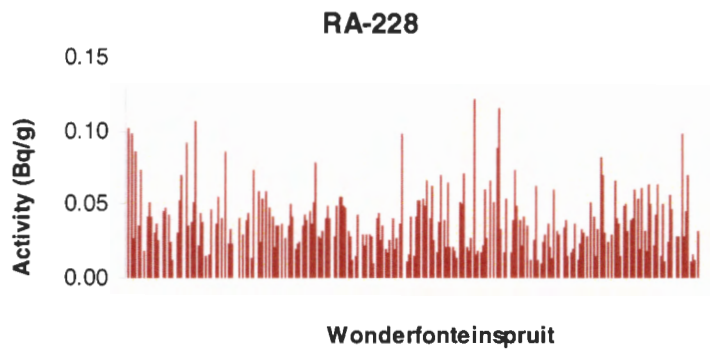

Figure 4.10 ^{228}Ra concentration plot of the WCA

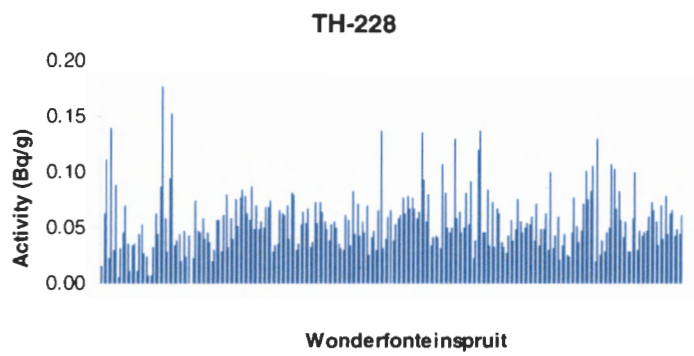

Figure 4.11 ^{228}Th concentration plot of the WCA

From Figures 4.10 and 4.11 it seems that there is not a fair correlation between ^{228}Ra and ^{228}Th which would have been expected due to their relative short half-lives compared to the "age" of the sediments. However, it can be seen from the database (Appendix 1) that the ^{228}Th data show relatively big uncertainty. Taking all available data into consideration, the following correlation for the ^{228}Th-^{228}Ra activity through linear regression has been obtained:

$[^{228}Th] = (1.538 \pm 0.036) . [^{228}Ra]; \qquad R^2 = 0.26$

However, taking the (arbitrarily) the first 70 data points sorted according to their detection uncertainty the following correlation has been obtained:

$[^{228}Th] = (1.444 \pm 0.036) . [^{228}Ra]; \qquad R^2 = 0.71$

which is still poor. The graphical representations for these combinations are shown in Figures 4.12 and 4.13.

This, however, still not give to the expected equilibrium between the two nuclides. Taking all available data into consideration and allowing the calculation of a "zero" value, that is a ^{228}Th background value, the following correlation for the ^{228}Th-^{228}Ra activity through linear regression were obtained:

$[^{228}Th] = (0.949 \pm 0.069) . [^{228}Ra] + 0.032; \qquad R^2 = 0.49$

Accordingly, although no ^{212}Pb or ^{212}Bi were observed in the background spectrum, and accordingly no background corrections were made to the sample data, it is possible that the environmental ^{220}Rn concentration in the counting room contributed to the calculated ^{228}Th concentrations as the levels of activity in the samples are in the same order as the environmental contribution.

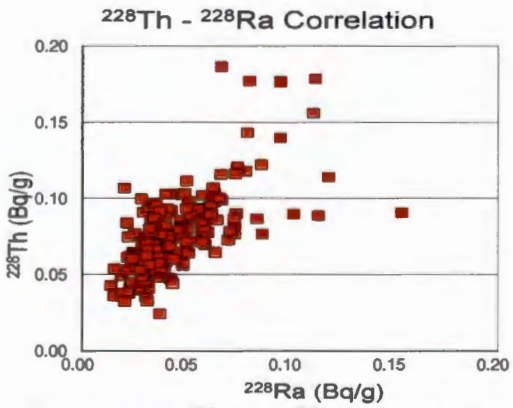

Figure 4.12 ^{228}Th – ^{228}Ra correlation (All data)

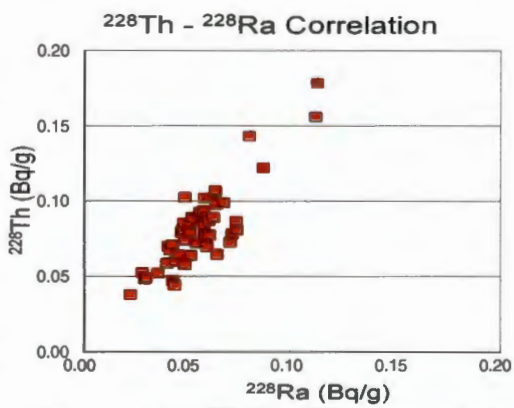

Figure 4.13 ^{228}Th – ^{228}Ra correlation (The first 70 data with reasonable measurement statistics)

4.4.4 ^{40}K

The average concentration of ^{40}K was fairly low at about 0.176 Bq/g. The maximum concentration observed at Coetzee Dam (S26 22.330 E27 14.301; Special A10), was about 1.128 Bq/g. The average concentration of ^{40}K was overall very low compared with the exclusion bill limit of natural radioactive radionuclides. The higher ^{40}K levels at certain dams may indicate pollution with fertilizer run-off from agricultural activities. The graphical representation of the ^{40}K concentrations over the catchment area is shown in Figure 4.14.

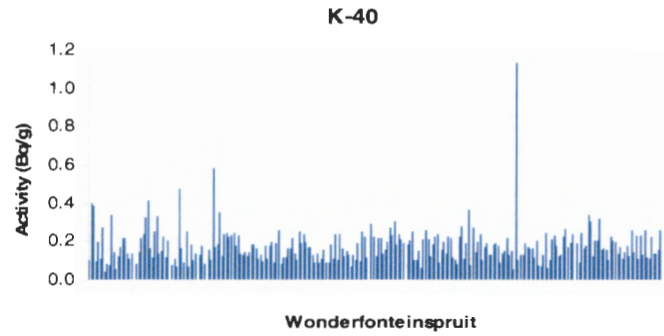

Figure 4.14 ^{40}K concentration plot of the WCA

4.4.5 ^{134}Cs and ^{137}Cs

Measured activities for these two nuclides were below the detection limit in the entire catchment area. The minimum detectable activities of ^{137}Cs and ^{134}Cs were about 0.012 Bq/g and 0.065 Bq/g respectively, indicating that these fission products are generally not of much concern. The graphical representations of the MDA-values over the catchment area are shown in Figures 4.15 and 4.16.

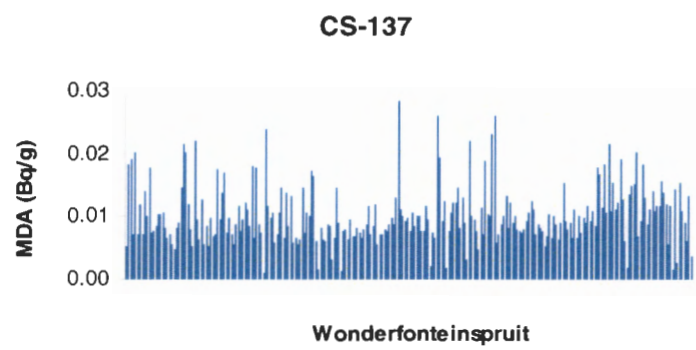

Figure 4.15 ^{137}Cs MDA plot of the WCA

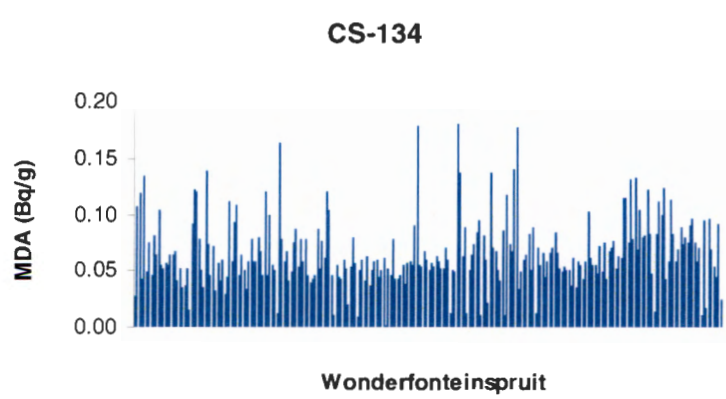

Figure 4.16 ^{134}Cs MDA plot of the WCA

The minimal detection of radiocesium in the Wonderfonteinspruit catchment area implied that it is not hazardous to the public.

4.4.6 Gross α and β activity

The measured gross alpha and beta activity profiles are shown in Figure 4.17 and 4.18 respectively. These profiles resemble those of the nuclides obtained for the ^{238}U series as given in paragraph 4.4.1, which is more or less expected if no large amounts of pure alpha and/or beta emitters are present in the samples.

The highest alpha activity measured was 21.8 Bq/g at the Coetzee Dam (S26 22.170 E27 14.492; D7.020) while the average alpha activity over the catchment area was about 4.12 Bq/g. Similar to the alpha activity, the highest beta activity was from the same sample of coordinates and field identity with an activity around 8.07 Bq/g, while the average beta activity in the catchment area was 1.39 Bq/g.

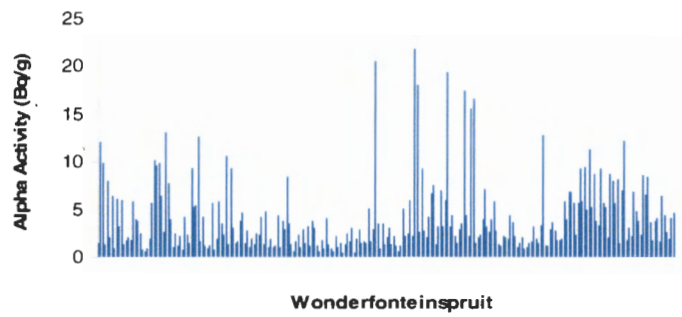

Figure 4.17 Gross alpha activity plot of the WCA

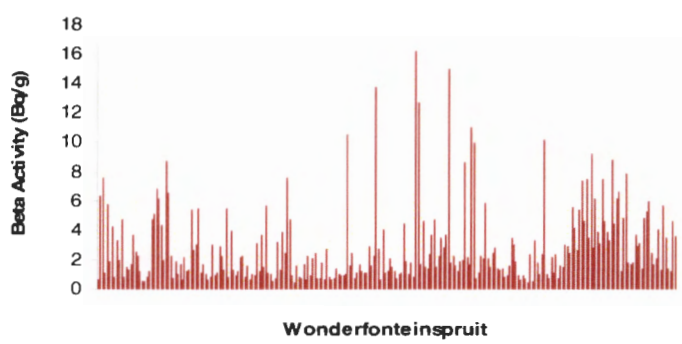

Figure 4.18 Gross beta activity plot of the WCA

In comparing two instruments, calculations from the gamma-spectrometric results and the measured alpha and beta activities of the samples were carried out. This was done upon assumption of the following equilibriums:

^{238}U-series	^{234}Th, ^{234m}Pa, ^{234}U and ^{230}Th in equilibrium with ^{238}U (the last nuclide may be questionable),
	^{226}Ra in equilibrium with all its short-lived daughters, and
	^{210}Bi and ^{210}Po in equilibrium with ^{210}Pb
^{235}U-series	^{227}Ac in equilibrium with its parent and all its daughters
^{232}Th series	^{228}Ra in equilibrium with its parent and direct daughter (the first may be questionable due to the low mobility of thorium)
	^{228}Th in equilibrium with all its daughters

Comparing these data with the measured gross alpha/beta data gave correlations, which are graphically presented in Figures 4.19 and 4.20.

Linear regression resulted the following:

Measured α-activity = (1.159 ± 0.043) · Calculated α-activity; R^2 = 0.45

Measured β-activity = (0,623 ± 0.024) · Calculated β-activity; R^2 = 0.42

This poor correlation is not readily explained and could possibly be sought in the first place in the preparation of calibration samples having different alpha and beta energies than the actual sediment samples and accordingly being less or more absorbed in the sample matrix.

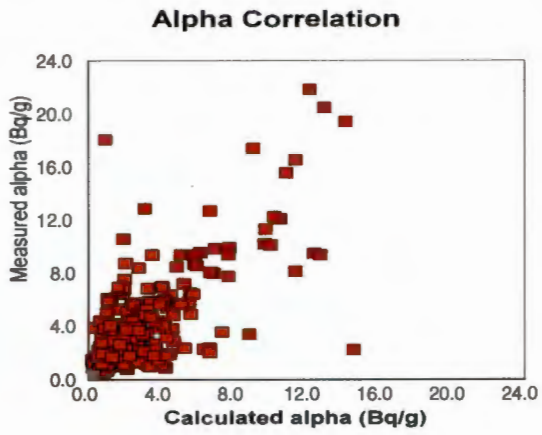

Figure 4.19 Measured-Calculated Alpha correlation

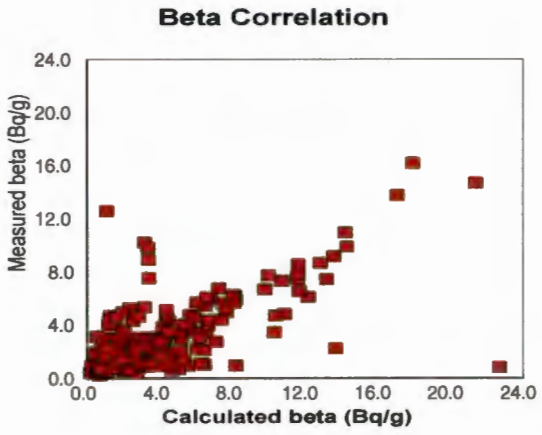

Figure 4.20 Measured-Calculated Beta correlation

4.5 Nuclide distribution in mosses in the Minsk area in Belarus

Due to the small sample size, only 10 samples, no statistical analysis were done on the data statistically and accordingly the data obtained will be given in a tabular form (Table 4.3).

Table 4.3 Activity concentrations found in some mosses

Sample No.	Activity concentrations (Bq/g)					
	^{40}K	^{137}Cs	^{210}Pb	^{226}Ra	Gross α	Gross β
1	0.32 ± 0.08	0.060 ± 0.008	0.24 ± 0.05	0.90 ± 0.04	2.21 ± 0.18	0.73 ± 0.03
2	0.34 ± 0.07	0.015 ± 0.007	0.42 ± 0.05	0.61 ± 0.03	0.82 ± 0.12	0.35 ± 0.03
3	0.43 ± 0.10	0.019 ± 0.008	0.42 ± 0.06	0.39 ± 0.03	0.54 ± 010	0.32 ± 0.03
4	0.46 ± 0.09	0.254 ± 0.013	0.48 ± 0.06	0.39 ± 0.03	0.84 ± 0.13	0.66 ± 0.04
5	0.31 ± 0.06	1.00 ± 0.02	0.64 ± 0.05	0.43 ± 0.03	0.73 ± 0.12	0.97 ± 0.04
6	0.27 ± 0.07	0.80 ± 0.02	0.54 ± 0.06	0.66 ± 0.04	0.73 ± 0.12	1.15 ± 0.04
7	0.26 ± 0.07	4.97 ± 0.06	0.51 ± 0.07	0.51 ± 0.04	1.29 ± 0.14	2.37 ± 0.05
8	0.37 ± 0.07	0.394 ± 0.014	0.50 ± 0.06	0.59 ± 0.04	0.91 ± 0.13	0.70 ± 0.04
9	0.34 ± 0.07	1.52 ± 0.03	0.54 ± 0.06	0.36 ± 0.03	0.87 ± 0.13	1.05 ± 0.04
10	0.29 ± 0.08	0.223 ± 0.012	0.49 ± 0.06	0.39 ± 0.03	0.66 ± 0.11	0.48 ± 0.03
Average	**0.33 ± 0.06**	**0.93 ± 1.36**	**0.48 ± 0.09**	**0.52 ± 0.15**	**0.96 ± 0.44**	**0.88 ± 0.54**

As a first order cautious comment, ^{226}Ra and ^{210}Pb seem to be in equilibrium and more or less evenly distributed over the sampling area along with ^{40}K, while ^{137}Cs is varying substantially over the area covered by the 10 samples. As stated in paragraph 2.4.2 under point 3 mosses do not have organs for the absorption of minerals from substrates, this is achieved mainly by precipitation. Accordingly, the observed ^{40}K, ^{226}Ra and ^{210}Pb concentrations could be caused by long-term environmental dust/rain deposition, while the ^{137}Cs deposition was most likely due to atmospheric deposition during a short period after the Chernobyl accident.

It also seems here that there are inconsistencies between the gamma spectrometric data and the gross alpha/beta results, which probably could be the subject of a future MSc-study.

5. POTENTIAL HAZARDS

Although it can be argued that the identified radionuclides may be adsorbed by the sediments and accordingly will not be very mobile, the often heard argument is that they may become mobile due to changing environmental circumstances. How they are mobilized is not very clear and so far only verified in a limited number of laboratory leach studies. (11)

However, as generally the elevated uranium concentrations and to a lesser extent also the ^{226}Ra activity may be taken into consideration cause this could be put into perspective for all nuclides observed in this study.

On assumption that due to changing environmental conditions and/or clean-up of the catchment area (as it is currently discussed) all nuclides will become equally mobile and end-up in the waterbody that is used by the local community, and this could be illustrated on a table with the relative dose received by the public from every individual nuclide similar to the approach by Faanhof. (42)

From the database the following average concentrations in Bq/g are observed for the catchment area studied.

Table 4.4 Average concentrations

	^{40}K	^{238}U	^{226}Ra	^{210}Pb	^{235}U	^{227}Ac	^{227}Th
Average	1.74×10^{-01}	9.34×10^{-01}	2.60×10^{-01}	2.71×10^{-01}	4.50×10^{-02}	1.07×10^{-01}	2.40×10^{-01}
Stand, dev.	9.87×10^{-02}	1.05×10^{00}	2.39×10^{-01}	2.96×10^{-01}	5.09×10^{-02}	2.05×10^{-01}	2.28×10^{-01}
Max	1.13×10^{00}	7.42×10^{00}	1.23×10^{00}	1.67×10^{00}	3.59×10^{-01}	9.23×10^{-01}	1.23×10^{00}
Min	4.04×10^{-02}	3.69×10^{-02}	1.91×10^{-02}	2.77×10^{-02}	1.78×10^{-03}	-1.53×10^{-03}	1.78×10^{-03}
Median	1.63×10^{-01}	6.30×10^{-01}	1.81×10^{-01}	1.61×10^{-01}	3.07×10^{-02}	3.64×10^{-02}	1.70×10^{-01}

Assuming that the average amount in Bq/g could be released to the waterbody in equal amounts in Bq/l, the dose to the general public were calculated, (Table 4.4). Further evaluation of the data relative to the concentrations of ^{238}U in secular equilibrium with ^{234}U the data were reduced to show the relative exposure of the public due to,

- ^{226}Ra and its short-lived daughters,
- ^{210}Pb and its daughters and
- ^{235}U and its short-lived daughter,
- ^{231}Pa and its short-lived daughters and
- ^{232}Th and its daughters.

Table 4.5 provides this overview setting the uranium contribution to unity (=1). From this it will be clear that uranium only and even in combination with ^{226}Ra will not provide the necessary information for dose evaluation and in doing so may strongly underestimate the dose received by the public.

From Tables 4.5 and 4.6 it can be deduced that although ^{226}Ra, ^{210}Pb and ^{232}Th are all about a quarter of the average ^{238}U activity they contribute about the same, 6,5 times and 4,5 times respectively to the total dose received from ^{238}U. It can be seen

that the relative contribution from ^{235}U is indeed negligible compared to ^{238}U, but it is generally overlooked that ^{231}Pa and its daughters can contribute substantially to the dose; although the average activity of the ^{231}Pa series nuclides is about 10% of the ^{238}U series they contribute about 2,5 times more to the total dose as ^{238}U does.

^{230}Th has been omitted from this evaluation as it was not detected and assumed to be in equilibrium with neither ^{238}U nor ^{226}Ra, although at similar activity ^{230}Th will have a double higher dose impact than the ^{238}U series nuclides.

Table 4.5 Potential relative to public exposure

	Yearly Dose via possible Ingestion for Members of the Public Dose in mSv/a							
	MR Sediments Sample	Water Consumption in liters per year Consumption x Activity x Dose per unit intake = Yearly Dose						Average Life-time Exposure mSv/a
	Activity mBq/L	< 1 a 200	1 - 2 a 260	2 -7 a 300	7 - 12 a 350	12 - 17 a 600	> 17 a 730	
U-238	**934.0**	0.064	0.029	0.022	0.022	0.038	0.031	0.030
Th-234	934.0	0.007	0.006	0.004	0.002	0.002	0.002	0.003
Pa-234m	934.0							
U-234	**934.0**	0.069	0.032	0.025	0.024	0.041	0.033	0.033
Th-230	**0.0**	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ra-226	**250.0**	0.235	0.062	0.047	0.070	0.225	0.051	0.067
Rn-222	250.0							
Po-218	250.0							
Pb-214	250.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Bi-214	250.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Po-214	250.0							
Pb-210	**271.0**	0.455	0.254	0.179	0.180	0.309	0.137	0.163
Bi-210	271.0	0.001	0.001	0.000	0.000	0.000	0.000	0.000
Po-210	**271.0**	1.409	0.620	0.358	0.247	0.260	0.237	0.276
U-235	**45.1**	0.003	0.002	0.001	0.001	0.002	0.002	0.002
Th-231	45.1	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pa-231	107.0	0.278	0.036	0.035	0.034	0.051	0.055	0.055
Ac-227	107.0	0.706	0.086	0.071	0.056	0.077	0.086	0.091
Th-227	**107.0**	0.006	0.002	0.001	0.001	0.001	0.001	0.001
Ra-223	**107.0**	0.113	0.031	0.018	0.017	0.024	0.008	0.013
Rn-219	107.0							
Po-215	107.0							
Pb-211	107.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Bi-211	107.0							
Tl-207	107.0							
Th-232	**240.0**	0.221	0.028	0.025	0.024	0.036	0.040	0.040
Ra-228	240.0	1.440	0.356	0.245	0.328	0.763	0.121	0.216
Ac-228	240.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Th-228	240.0	0.178	0.023	0.016	0.013	0.014	0.013	0.016
Ra-224	240.0	0.130	0.041	0.025	0.022	0.029	0.011	0.017
Rn-220	240.0							
Po-216	240.0							
Pb-212	240.0	0.007	0.004	0.002	0.002	0.002	0.001	0.001
Bi-212	240.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Po-212								
Tl-208								
Total mSv/a	**Total mSv/a**	**5.32**	**1.61**	**1.07**	**1.04**	**1.87**	**0.83**	**1.02**
K-40	174.0	0.002	0.002	0.001	0.001	0.001	0.001	0.001

Table 4.6 Relative exposure to average nuclide concentrations found in the sediments

Dose in mSv/a relative to uranium							
	Age Group						Average Life-time
Nuclides concerned	< 1 a	1 - 2 a	2 -7 a	7 - 12 a	12 - 17 a	> 17 a	**Exposure**
U-238, Th-234, U-234	1.00×10^{0}	1.00×10^{0}	1.00×10^{0}	1.00×10^{0}	1.00×10^{0}	1.00×10^{0}	1.00×10^{0}
Ra-226, Pb-214, Bi-214	1.68×10^{0}	9.36×10^{-1}	9.18×10^{-1}	1.43×10^{0}	2.77×10^{0}	7.70×10^{-1}	1.02×10^{0}
Pb-210, Bi-210, Po-210	1.33×10^{1}	1.31×10^{1}	1.06×10^{1}	8.75×10^{0}	7.00×10^{0}	5.63×10^{0}	6.64×10^{0}
U-235, Th-231	2.28×10^{-2}	2.33×10^{-2}	2.30×10^{-2}	2.32×10^{-2}	2.34×10^{-2}	2.35×10^{-2}	2.34×10^{-2}
Pa-231, Ac-227, Th-227, Ra-223, Pb-211	7.88×10^{0}	2.32×10^{0}	2.47×10^{0}	2.22×10^{0}	1.88×10^{0}	2.26×10^{0}	2.41×10^{0}
Th-232, Ra-228, Ac-228, Th-228, Ra-224, Pb-212, Bi-212	1.41×10^{1}	6.77×10^{0}	6.18×10^{0}	7.95×10^{0}	1.04×10^{1}	2.81×10^{0}	4.38×10^{0}
K-40	1.54×10^{-2}	2.85×10^{-2}	2.16×10^{-2}	1.62×10^{-2}	9.75×10^{-3}	1.19×10^{-2}	1.30×10^{-2}

6. CONCLUSIONS AND RECOMMENDATIONS

Regarding the age of the sediments, since the first gold mining activities started some 125 years ago, it is shown that the medium lived nuclides ^{210}Pb and ^{227}Ac, both with a half-life in the order of 20 years, can be taken to be in equilibrium with their respective long-lived parents ^{226}Ra and ^{231}Pa. The sometimes negative activity values for ^{227}Ac were as a result of interference corrections done and since the nuclide in particular has a high dose conversion factor it was important to be measured. However, the assumption of ^{232}Th being in equilibrium with its direct daughters ^{228}Ra and ^{228}Th, should be verified through the determination of ^{232}Th using other analytical techniques, for example by neutron activation analysis.

Measurement problem in the gamma spectrometry would have been caused by the attenuation considering the mass thickness of the sample with the average mass of 30 g. However this may have been corrected by the Genie-2000 software when analysing the sample during the counting period. Electronic vibrations and the background affect the overall resulting concentration value and since calibrations were carried out the factor value contributing to results was very less, thus negligible.

Measurement of gross alpha and beta activities alone will not be enough to evaluate the contamination in the area investigated. Differences in measured gross alpha and beta data with the calculated data from gamma spectrometry may have risen from inhomogeneity in sub-samples taken for the respective analysis. This should be investigated further to obtain insight in the particle size of the sediments after various stages of homogenization and analyses of varying quantities of sub-samples between around 300 mg (normally used for neutron activation analysis) up to around 50 g (typically used in gamma spectrometry). It could well be that decayed plant material and direct deposition of wind-blown or run-off from tailings dams are difficult to homogenize at small sample quantities.

Evaluation of the potential radiological hazard should not be based on uranium and radium data only but all nuclides of the natural series should be taken into consideration until proven not to be present in concentrations of substance.

No substantial fall-out from ^{137}Cs and ^{134}Cs was observed in the majority of samples and only in one case showed a positive value for ^{134}Cs and in two samples values for ^{137}Cs, which were all close to the lower limit of determination and according showed large uncertainties (25-55%). Longer counting times on a reduced suite of samples could be done in a follow-up study to obtain a fingerprint of the ^{137}Cs data, which are also of interest in soil studies.

On the other hand the samples from the Belarus area did contain substantial amount of ^{137}Cs but no ^{134}Cs indicating that the activity was deposited probably only from the Chernobyl accident some 3 decades ago. However, the somewhat unexpected observed concentration of ^{226}Ra in apparent equilibrium with ^{210}Pb of about 0,5 Bq/g indicate that this could be caused by long-term environmental dust/rain deposition as mosses do not have organs for the absorption of minerals from substrates.

Rehabilitation of the Wonderfonteinspruit catchment area would be recommenmded; looking at the number of waste dumps that are surrounding this river. This could be partly achieved by regular monitoring of water entering this river system from mining activities. The main common factor between sediments and mosses are that they have the ability to accumulate radionuclides over a long period of time. They are

definitely good indicators of the surrounding radiological impact which poses potential adverse effects to the public.

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LIST of Abbreviations

α	alpha particle
β	beta particle
γ	gamma ray
INAA	Instrumentation Neutron Activation Analysis
NORM	Natural Occurring Radioactive Material
WCA	Wonderfonteinspruit Catchment Area

Appendix 1 The data base for NORM nuclides as measured by gamma spectrometry

GPS Coordinates	U-238		RA-226		PB-210		U-235		AC-227		RA-228		TH-228	
	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 19.038 E27 23.395	9.34E-01	8.10E-02	2.96E-02	2.89E-03			4.51E-02	5.41E-03					1.64E-02	2.28E-03
S26 19.039 E27 23.302	1.75E+00	2.54E-01	1.23E+00	2.07E-02	1.38E+00	8.02E-02	8.47E-02	1.22E-02	4.32E-02	1.62E-02	1.23E+00	2.07E-02	1.77E-01	9.56E-03
S26 19.039 E27 23.302	2.11E+00	4.43E-01	8.44E-01	1.76E-02	8.58E-01	6.96E-02	1.02E-01	2.14E-02			8.44E-01	1.76E-02	8.94E-02	7.00E-03
S26 19.039 E27 23.337	2.55E-01	2.62E-02	1.18E-01	4.79E-03	6.73E-02	1.68E-02	1.23E-02	1.27E-03			1.18E-01	4.79E-03	4.08E-02	3.46E-03
S26 19.039 E27 23.337	1.54E+00	3.93E-01	6.97E-01	1.72E-02	8.37E-01	6.88E-02	7.42E-02	1.90E-02			6.97E-01	1.72E-02	1.87E-01	1.07E-02
S26 19.039 E27 23.365	6.77E-01	9.26E-02	1.18E-01	5.11E-03	1.63E-01	2.37E-02	3.27E-02	4.47E-03			1.18E-01	5.11E-03	4.73E-02	3.93E-03
S26 19.039 E27 23.365	1.39E+00	1.92E-01	3.71E-01	9.76E-03	3.66E-01	4.14E-02	6.73E-02	9.26E-03	1.88E-02	1.34E-02	3.71E-01	9.76E-03	1.43E-01	7.21E-03
S26 19.042 E27 23.428	8.13E-01	1.06E-01	6.29E-01	1.27E-02	4.51E-01	4.45E-02	-6.38E-03	2.99E-04			4.06E-01	5.32E-02		
S26 19.042 E27 23.428	1.96E-01	3.04E-02	9.84E-02	4.61E-03	9.88E-02	1.68E-02	-2.30E-02	1.41E-02			9.84E-02	4.61E-03	4.92E-02	4.39E-03
S26 19.042 E27 23.428	5.98E-01	5.56E-02	3.46E-01	9.51E-03	3.03E-01	3.35E-02	2.89E-02	2.69E-03			3.46E-01	9.51E-03	4.61E-02	4.41E-03
S26 19.055 E27 23.411	2.29E-01	3.27E-02	7.88E-02	4.64E-03	7.59E-02	1.95E-02	1.11E-02	1.58E-03	3.34E-02	1.58E-02	7.88E-02	4.64E-03	6.41E-02	4.71E-03
S26 19.055 E27 23.411	3.88E-01	5.41E-02	1.34E-01	6.08E-03	1.82E-01	2.75E-02	1.88E-02	2.61E-03			1.34E-01	6.08E-03	8.88E-02	5.50E-03
S26 19.055 E27 23.411	3.88E-01	5.75E-02	1.01E-01	5.42E-03	1.37E-01	2.36E-02	1.87E-02	2.78E-03			1.01E-01	5.42E-03	5.62E-02	4.56E-03
S26 19.055 E27 23.411	3.88E-01	6.12E-02	2.27E-01	9.06E-03	2.35E-01	3.56E-02	1.87E-02	2.96E-03			1.87E-02	2.96E-03		
S26 19.055 E27 23.411	4.09E-01	5.77E-02	8.29E-02	4.68E-03	1.18E-01	2.40E-02	1.98E-02	2.79E-03			8.29E-02	4.68E-03		
S26 19.055 E27 23.411	1.15E+00	1.47E-01	5.73E-01	1.46E-02	6.81E-01	5.80E-02	-1.47E-02	5.87E-04	4.09E-02	1.27E-02	5.73E-01	1.46E-02	1.05E-01	7.14E-03
S26 19.055 E27 23.411	6.18E-01	5.80E-02	2.96E-01	8.58E-03	3.32E-01	3.70E-02	3.49E-02	4.80E-03			2.96E-01	8.58E-03	7.13E-02	4.93E-03
S26 19.055 E27 23.411	7.23E-01	9.94E-02	2.42E-01	7.85E-03	2.67E-01	3.22E-02	1.10E-02	1.78E-03			2.42E-01	7.85E-03	5.62E-02	4.50E-03
S26 19.056 E27 23.456	2.28E-01	3.68E-02	8.90E-02	4.63E-03	5.34E-02	1.76E-02	3.10E-03	7.93E-04			8.90E-02	4.63E-03	4.26E-02	4.02E-03
S26 19.056 E27 23.456	6.42E-02	1.64E-02	3.67E-02	3.60E-03			1.12E-02	1.63E-03			3.67E-02	3.60E-03	4.46E-02	3.75E-03
S26 19.057 E27 23.429	2.32E-01	3.38E-02	5.40E-02	3.53E-03	5.72E-02	1.33E-02	6.32E-03	1.03E-03						
S26 19.057 E27 23.429	1.31E-01	2.14E-02	2.45E-02	2.59E-03			-3.50E-03	2.29E-04			2.45E-02	2.59E-03		
S26 19.062 E27 23.282	1.23E+00	2.54E-01	4.33E-01	1.16E-02	4.82E-01	4.56E-02	8.57E-03	1.84E-03			4.33E-01	1.16E-02	1.03E-01	7.05E-03
S26 19.062 E27 23.282	1.77E-01	3.80E-02	9.81E-02	5.31E-03	8.88E-02	1.98E-02	7.35E-02	1.63E-02	8.64E-03	8.64E-03	9.81E-02	5.31E-03	5.79E-02	4.50E-03
S26 19.062 E27 23.336	1.52E+00	3.37E-01	1.08E+00	2.07E-02	1.31E+00	8.27E-02	-4.21E-02	1.77E-02	4.62E-02	2.41E-02	1.08E+00	2.07E-02	2.17E-01	1.11E-02
S26 19.062 E27 23.336	1.99E+00	3.33E-01	5.60E-01	1.56E-02	4.97E-01	6.26E-02	-1.21E-02	2.25E-02	8.71E-02	3.71E-02	9.61E-02	1.61E-02	1.42E-01	8.77E-03
S26 19.062 E27 23.336	1.01E+00	1.35E-01	9.08E-01	1.61E-02	9.03E-01	6.42E-02	4.89E-02	6.54E-03	1.63E-02	1.72E-02	9.08E-01	1.61E-02	7.24E-02	5.35E-03
S26 19.063 E27 23.456	6.84E-01	1.55E-01	1.54E-01	6.01E-03	1.24E-01	2.55E-02	3.31E-02	7.51E-03			1.54E-01	6.01E-03	5.06E-02	4.09E-03
S26 19.063 E27 23.456	1.37E+00	2.66E-01	3.00E-01	9.05E-03	2.89E-01	4.03E-02	6.61E-02	1.29E-02			3.00E-01	9.05E-03	9.40E-02	6.21E-03
S26 19.064 E27 23.308	2.67E+00	4.16E-01	1.06E+00	1.03E-02	1.33E+00	4.83E-02	1.29E-01	2.01E-02	1.14E-02	6.17E-03	1.06E+00	1.03E-02	1.02E-01	2.28E-03
S26 19.064 E27 23.308	2.26E+00	4.17E-01	7.06E-01	1.79E-02	8.00E-01	7.44E-02	1.09E-01	2.02E-02	1.93E-02	1.59E-02	7.06E-01	1.79E-02	1.79E-01	9.15E-03

Empty spaces indicate a lower limit of determination value was obtained. See the end of the Table to find an indication of the lower limits

GPS Coordinates	U-238		RA-226		PB-210		U-235		AC-227		RA-228		TH-228	
	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 19.064 E27 23.400	1.29E-01	2.23E-02	4.50E-02	3.41E-03			-1.61E-02	5.68E-04			4.50E-02	3.41E-03		
S26 19.064 E27 23.400	3.63E-01	5.25E-02	2.49E-01	8.76E-03	2.40E-01	3.35E-02	1.76E-02	2.54E-03			2.49E-01	8.76E-03		
S26 19.064 E27 23.429	7.23E-02	1.68E-02	4.62E-02	3.16E-03	5.48E-02	1.19E-02	-3.63E-03	1.13E-02	7.66E-03	6.16E-03	3.61E-02	8.39E-03	5.35E-02	4.21E-03
S26 19.064 E27 23.429	3.87E-01	5.91E-02	2.39E-01	8.54E-03	1.86E-01	3.40E-02	1.87E-02	2.85E-03			2.39E-01	8.54E-03		
S26 19.064 E27 23.429	4.89E-01	4.63E-02	2.13E-01	6.90E-03	1.99E-01	2.91E-02	2.36E-02	2.24E-03			2.13E-01	6.90E-03		
S26 19.065 E27 23.345	7.81E-01	7.36E-02	1.70E-01	6.57E-03	1.72E-01	2.86E-02	3.77E-02	3.55E-03			1.70E-01	6.57E-03	5.59E-02	4.53E-03
S26 19.065 E27 23.345	1.18E-01	1.91E-02	4.84E-02	3.36E-03	4.88E-02	1.19E-02	5.70E-03	9.24E-04	5.24E-02	3.19E-02	4.84E-02	3.36E-03	3.56E-02	3.32E-03
S26 19.070 E27 23.445	1.41E+00	1.90E-01	7.83E-01	1.65E-02	9.75E-01	6.83E-02	-5.35E-03	2.73E-04			7.83E-01	1.65E-02	5.83E-02	4.24E-03
S26 19.070 E27 23.445	1.41E-01	2.37E-02	8.25E-02	4.21E-03	8.49E-02	1.70E-02	1.76E-02	8.77E-03			7.07E-02	1.19E-02		
S26 19.070 E27 23.445	7.14E-01	1.03E-01	3.35E-01	8.80E-03	4.01E-01	3.43E-02	-5.08E-02	1.07E-03	2.98E-02	1.52E-02	3.35E-01	8.80E-03	9.98E-02	6.77E-03
S26 19.070 E27 23.445	3.68E-01	3.42E-02	1.66E-01	5.98E-03	1.71E-01	2.18E-02	-9.99E-03	8.50E-03	1.90E-02	7.81E-03	1.66E-01	5.98E-03	2.41E-02	2.98E-03
S26 19.070 E27 23.456	8.59E-01	7.80E-02	4.91E-01	1.23E-02	6.15E-01	5.02E-02	-3.18E-02	8.00E-04			4.91E-01	1.23E-02	7.65E-02	5.73E-03
S26 19.070 E27 23.456	1.11E+00	2.62E-01	1.10E+00	1.89E-02	8.35E-01	6.26E-02	-4.47E-02	1.93E-02					5.62E-02	5.44E-03
S26 19.087 E27 23.283	6.77E-01	6.25E-02	2.63E-01	8.01E-03	1.15E-01	2.78E-02	3.27E-02	3.02E-03			2.63E-01	8.01E-03	5.92E-02	4.65E-03
S26 19.087 E27 23.283	3.02E-01	4.46E-02	5.43E-02	3.62E-03	6.11E-02	1.59E-02	1.46E-02	2.16E-03			5.43E-02	3.62E-03	4.43E-02	3.51E-03
S26 19.089 E27 23.308	9.34E-01	0.00E+00	1.91E-02	2.49E-03			4.51E-02	5.45E-03			1.91E-02	2.49E-03	4.24E-02	3.65E-03
S26 19.089 E27 23.308	3.06E-01	4.33E-02	9.61E-02	4.58E-03	6.60E-02	1.70E-02	1.48E-02	2.09E-03					1.97E-02	2.48E-03
S26 19.089 E27 23.336	2.06E-01	3.44E-02	9.18E-02	5.37E-03	9.89E-02	2.22E-02	-9.82E-03	3.94E-04			9.18E-02	5.37E-03	7.34E-02	5.35E-03
S26 19.089 E27 23.336	8.61E-01	1.16E-01	3.54E-01	9.69E-03	3.99E-01	3.90E-02	4.70E-02	1.35E-02	3.33E-02	7.99E-03	3.54E-01	9.69E-03	6.91E-02	5.24E-03
S26 19.089 E27 23.336	1.17E-01	2.61E-02	1.51E-01	6.09E-03	6.67E-02	2.18E-02	-5.95E-03	3.48E-04					4.39E-02	4.03E-03
S26 19.090 E27 23.372	1.48E-01	2.34E-02	2.90E-01	8.46E-03	1.60E-01	2.51E-02	-1.88E-02	5.48E-04			2.90E-01	8.46E-03	8.62E-02	5.78E-03
S26 19.090 E27 23.372	4.94E-01	6.80E-02	5.62E-01	1.22E-02	3.70E-01	3.72E-02	-2.30E-02	1.25E-02			2.39E-02	3.29E-03	3.75E-02	3.67E-03
S26 19.090 E27 23.372	9.94E-01	1.70E-01	2.66E-01	8.83E-03	3.38E-01	3.57E-02	3.02E-02	1.14E-02			2.66E-01	8.83E-03	6.70E-02	5.26E-03
S26 19.092 E27 23.344	1.15E+00	2.93E-01	9.85E-01	1.90E-02	9.58E-01	7.01E-02	2.16E-02	8.05E-03					5.02E-02	3.95E-03
S26 19.092 E27 23.344	3.75E-01	5.37E-02	1.06E-01	4.88E-03	9.98E-02	2.14E-02	-6.39E-02	1.23E-03	7.28E-02	2.13E-02	1.06E-01	4.88E-03	9.00E-02	6.68E-03
S26 19.092 E27 23.344	1.77E-01	2.60E-02	4.07E-02	3.44E-03			2.96E-03	1.91E-03			4.07E-02	3.44E-03	4.27E-02	3.58E-03
S26 19.129 E27 23.255	6.69E-01	9.57E-02	6.73E-01	1.61E-02	9.34E-01	6.61E-02	-1.40E-02	1.96E-02	5.24E-02	1.72E-02	6.73E-01	1.61E-02	1.03E-01	7.51E-03
S26 19.130 E27 23.253	3.61E-01	5.02E-02	2.26E-01	7.24E-03	1.53E-01	2.66E-02	2.34E-02	1.01E-02			2.26E-01	7.24E-03	6.44E-02	4.52E-03
S26 19.132 E27 21.622	8.95E-02	2.04E-02	6.47E-02	4.25E-03	7.16E-02	1.81E-02	2.91E-03	2.08E-03			6.47E-02	4.25E-03	1.02E-01	1.79E-03
S26 19.132 E27 21.622	2.79E-01	5.28E-02	8.32E-02	1.32E-03	8.23E-02	5.80E-03	1.71E-02	2.40E-03	-8.35E-04	2.32E-03	8.32E-02	1.32E-03	1.02E-01	5.57E-03
S26 19.133 E27 21.596	5.41E-01	6.78E-02	2.93E-01	1.62E-02	1.61E-01	5.58E-02	-1.90E-02	1.05E-03			2.93E-01	1.62E-02	7.06E-02	5.47E-03
S26 19.133 E27 21.596	5.72E-01	8.04E-02	4.21E-01	1.03E-02	2.86E-01	3.38E-02	-6.13E-03	1.25E-02			2.76E-02	3.89E-03	8.56E-02	1.07E-02
S26 19.133 E27 21.608	5.36E-01	7.12E-02	2.55E-01	8.14E-03	1.29E-01	2.80E-02	-9.97E-05	2.24E-03			2.55E-01	8.14E-03	7.41E-02	5.43E-03
S26 19.133 E27 21.608	7.25E-02	1.74E-02	7.94E-02	4.90E-03			3.50E-03	8.41E-04			7.94E-02	4.90E-03	8.37E-02	5.52E-03
S26 19.991 E27 20.517	6.95E-02	1.41E-02	6.19E-02	4.13E-03	5.14E-02	1.63E-02	-4.01E-03	2.68E-04			6.19E-02	4.13E-03	5.63E-02	4.43E-03

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GPS Coordinates	U-238		RA-226		PB-210		U-235		AC-227		RA-228		TH-228	
	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 20.001 E27 20.480	3.02E-01	4.46E-02	1.49E-01	6.85E-03	9.02E-02	2.37E-02	-6.71E-04	2.11E-03			1.49E-01	6.85E-03	6.84E-02	5.40E-03
S26 20.001 E27 20.480	1.42E-01	2.33E-02	1.11E-01	5.28E-03	3.26E-02	1.61E-02	6.88E-03	1.13E-03			1.11E-01	5.28E-03	9.06E-02	5.42E-03
S26 20.089 E27 20.447	1.23E+00	2.24E-01	2.45E-01	9.13E-03	1.86E-01	3.46E-02	5.66E-02	1.40E-02					7.25E-02	5.96E-03
S26 20.139 E27 20.390	1.54E+00	2.40E-01	2.55E-01	8.92E-03	2.70E-01	3.90E-02	-1.02E-02	3.79E-04			2.55E-01	8.92E-03	8.85E-02	6.13E-03
S26 20.139 E27 20.390	3.75E-01	5.20E-02	1.57E-01	5.85E-03	1.64E-01	2.20E-02	1.81E-02	2.51E-03			1.57E-01	5.85E-03	4.17E-02	3.82E-03
S26 20.140 E27 19.991	1.31E-01	1.31E-02	1.41E-01	5.90E-03	9.31E-02	2.15E-02	6.35E-03	6.33E-04			1.41E-01	5.90E-03	8.53E-02	5.06E-03
S26 20.140 E27 19.991	2.06E+00	2.81E-01	3.44E-01	9.49E-03	3.23E-01	4.07E-02	9.93E-02	1.36E-02			3.44E-01	9.49E-03	9.18E-02	5.69E-03
S26 20.140 E27 20.485	4.50E-01	6.57E-02	2.74E-02	2.82E-03	4.24E-02	1.42E-02	2.17E-02	3.17E-03			2.74E-02	2.82E-03	3.97E-02	3.49E-03
S26 20.140 E27 20.485	3.26E-01	5.05E-02	6.50E-02	4.06E-03	6.24E-02	1.52E-02	1.58E-02	2.44E-03			6.50E-02	4.06E-03	4.13E-02	3.63E-03
S26 20.140 E27 20.485	1.80E-01	2.85E-02	3.89E-02	3.18E-03	3.33E-02	1.21E-02	8.69E-03	1.38E-03			3.89E-02	3.18E-03	3.75E-02	3.33E-03
S26 20.143 E27 20.110	1.20E+00	2.44E-01	4.04E-01	1.14E-02	3.09E-01	4.02E-02	5.77E-02	1.18E-02			4.04E-01	1.14E-02	8.50E-02	5.06E-03
S26 20.143 E27 20.110	9.34E-01	0.00E+00	4.06E-02	3.38E-03	7.21E-02	1.53E-02	4.51E-02	5.49E-03			4.06E-02	3.38E-03	7.52E-02	5.88E-03
S26 20.145 E27 19.870	1.24E+00	2.58E-01	2.49E-01	8.10E-03	3.19E-01	3.63E-02	5.97E-02	1.24E-02			2.49E-01	8.10E-03	8.54E-02	5.56E-03
S26 20.145 E27 19.870	2.51E-01	4.48E-02	5.29E-02	3.82E-03	5.02E-02	1.96E-02	1.21E-02	2.16E-03			5.29E-02	3.82E-03	8.89E-02	5.24E-03
S26 20.145 E27 20.049	1.61E+00	3.30E-01	4.18E-01	1.19E-02	4.01E-01	4.43E-02	7.78E-02	1.59E-02			4.18E-01	1.19E-02	9.76E-02	7.32E-03
S26 20.145 E27 20.049	8.30E-01	7.42E-02	2.20E-01	7.20E-03	1.84E-01	3.04E-02	4.01E-02	3.58E-03	5.93E-02	3.49E-02	2.20E-01	7.20E-03	4.79E-02	4.11E-03
S26 20.145 E27 20.049	2.96E+00	5.59E-01	5.83E-01	1.48E-02	7.44E-01	6.73E-02	1.43E-01	2.70E-02			5.83E-01	1.48E-02	1.14E-01	7.04E-03
S26 20.187 E27 20.110	1.50E-01	2.54E-02	1.17E-01	5.08E-03	5.45E-02	1.51E-02	7.27E-03	1.23E-03			1.17E-01	5.08E-03	4.90E-02	1.20E-03
S26 20.187 E27 20.110	3.97E-02	6.18E-03	4.39E-02	1.00E-03	3.95E-02	4.33E-03	-2.85E-03	6.49E-05			4.39E-02	1.00E-03	3.97E-02	3.46E-03
S26 20.192 E27 19.930	7.70E-02	1.63E-02	5.61E-02	3.61E-03	6.86E-02	1.49E-02	1.38E-02	3.31E-03			5.61E-02	3.61E-03	5.36E-02	4.20E-03
S26 20.192 E27 19.930	6.45E-01	1.30E-01	1.23E-01	5.63E-03	9.71E-02	2.39E-02	-1.82E-03	1.49E-03			1.23E-01	5.63E-03	6.98E-02	4.55E-03
S26 20.193 E27 19.799	5.35E-01	7.71E-02	1.53E-01	5.96E-03	1.88E-01	2.55E-02	2.84E-03	2.12E-03			1.53E-01	5.96E-03	8.06E-02	4.95E-03
S26 20.193 E27 19.799	1.40E-01	2.52E-02	5.20E-02	3.49E-03	6.42E-02	1.77E-02	2.18E-02	7.99E-03			5.20E-02	3.49E-03	8.93E-02	5.28E-03
S26 20.194 E27 20.173	6.74E-01	1.24E-01	1.64E-01	2.61E-03	1.23E-01	9.00E-03	-4.20E-04	2.21E-03			3.25E-02	5.98E-03	4.56E-02	4.43E-03
S26 20.194 E27 20.173	1.71E-01	2.74E-02	6.06E-02	4.32E-03			3.70E-02	5.00E-03			6.06E-02	4.32E-03	4.48E-02	1.48E-03
S26 20.194 E27 20.383	8.88E-01	1.84E-01	3.06E-01	1.01E-02	2.25E-01	3.52E-02	1.67E-03	2.33E-03			3.06E-01	1.01E-02	9.34E-02	5.40E-03
S26 20.194 E27 20.383	1.06E-01	1.71E-02	6.27E-02	4.46E-03	8.12E-02	1.63E-02	1.51E-02	1.14E-02			6.27E-02	4.46E-03	8.04E-02	6.21E-03
S26 20.195 E27 19.870	7.82E-02	1.94E-02	5.13E-02	9.56E-04	5.06E-02	4.30E-03	1.73E-02	3.56E-03			5.13E-02	9.56E-04	7.94E-02	1.46E-03
S26 20.195 E27 19.870	6.88E-01	1.60E-01	1.48E-01	6.19E-03	1.38E-01	2.62E-02	-1.55E-03	1.40E-03	-1.53E-03	7.78E-04	1.48E-01	6.19E-03	9.23E-02	5.41E-03
S26 20.195 E27 19.990	4.98E-02	1.32E-02	7.92E-02	4.81E-03	6.75E-02	1.64E-02	-2.43E-03	1.83E-03			7.92E-02	4.81E-03	7.98E-02	5.43E-03
S26 20.195 E27 19.990	6.73E-01	1.33E-01	1.01E-01	5.32E-03	1.17E-01	2.40E-02	3.25E-02	6.43E-03			1.01E-01	5.32E-03	5.55E-02	4.45E-03
S26 20.242 E27 19.870	9.34E-01	8.10E-02	5.36E-02	3.30E-03	7.06E-02	1.50E-02	4.51E-02	5.39E-03			5.36E-02	3.30E-03	6.26E-02	4.29E-03
S26 20.242 E27 19.870	8.56E-01	1.79E-01	2.39E-01	7.16E-03	2.44E-01	2.79E-02	4.14E-02	8.64E-03			2.39E-01	7.16E-03	5.37E-02	3.78E-03
S26 20.244 E27 20.049	2.53E-01	4.05E-02	6.61E-02	3.86E-03	6.05E-02	1.75E-02	1.22E-02	1.96E-03			6.61E-02	3.86E-03	5.62E-02	4.36E-03
S26 20.244 E27 20.049	5.05E-02	1.54E-02	3.83E-02	3.52E-03	7.70E-02	1.83E-02	2.44E-03	7.45E-04			3.83E-02	3.52E-03	5.05E-02	3.98E-03

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GPS Coordinates	U-238		RA-226		PB-210		U-235		AC-227		RA-228		TH-228	
	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 20.245 E27 20.110	1.03E-01	2.36E-02	5.54E-02	4.35E-03	4.73E-02	1.63E-02	-3.59E-03	2.82E-04					4.06E-02	4.51E-03
S26 20.245 E27 20.110	4.72E-01	7.09E-02	1.23E-01	5.55E-03	1.61E-01	2.76E-02	2.27E-02	8.55E-03			1.23E-01	5.55E-03	4.46E-02	3.85E-03
S26 20.247 E27 19.930	1.27E-01	2.80E-02	1.03E-01	5.20E-03	8.47E-02	2.06E-02	7.64E-03	2.24E-03			1.03E-01	5.20E-03	7.08E-02	4.99E-03
S26 20.247 E27 19.930	3.39E-01	4.80E-02	6.11E-02	3.60E-03	8.45E-02	1.61E-02	1.68E-03	2.26E-03			6.11E-02	3.60E-03	3.51E-02	3.26E-03
S26 20.248 E27 19.991	9.34E-01	8.20E-02	9.36E-02	5.22E-03	4.30E-02	1.90E-02	-6.07E-03	3.38E-04			9.36E-02	5.22E-03	4.88E-02	1.16E-03
S26 20.248 E27 19.991	3.05E-01	5.07E-02	9.71E-02	1.48E-03	8.73E-02	5.86E-03	9.87E-03	1.61E-03			9.71E-02	1.48E-03	7.50E-02	5.53E-03
S26 20.255 E27 19.798	5.59E-01	5.98E-02	2.75E-01	7.67E-03	2.40E-01	2.74E-02	2.11E-02	1.03E-02			2.75E-01	7.67E-03	1.07E-01	5.71E-03
S26 20.303 E27 20.390	6.26E-01	8.03E-02	2.87E-01	9.37E-03	3.52E-01	3.81E-02	9.75E-03	3.00E-03			2.87E-01	9.37E-03	9.29E-02	6.23E-03
S26 20.303 E27 20.390	4.33E-01	5.96E-02	1.20E-01	5.51E-03	1.29E-01	2.45E-02	-1.86E-02	6.07E-04			1.20E-01	5.51E-03	5.75E-02	4.32E-03
S26 20.306 E27 19.870	1.16E-01	1.90E-02	5.61E-02	3.69E-03	3.64E-02	1.57E-02	-3.63E-03	2.39E-04			5.61E-02	3.69E-03	7.06E-02	4.34E-03
S26 20.306 E27 19.870	3.26E-01	4.52E-02	8.59E-02	4.22E-03	9.74E-02	1.94E-02	1.35E-02	8.14E-03			8.59E-02	4.22E-03	6.37E-02	4.29E-03
S26 20.451 E27 19.645	5.67E-01	7.74E-02	1.07E-01	5.12E-03	8.51E-02	2.15E-02	1.12E-02	3.02E-03			1.07E-01	5.12E-03	5.86E-02	4.27E-03
S26 20.458 E27 19.645	1.29E-01	1.38E-02	8.95E-02	5.11E-03	1.10E-01	2.19E-02	2.25E-02	9.80E-03			8.95E-02	5.11E-03	7.87E-02	5.23E-03
S26 20.465 E27 19.645	1.01E-01	1.21E-02	1.92E-01	6.19E-03	9.88E-02	1.95E-02	3.93E-03	2.83E-03			1.92E-01	6.19E-03	3.23E-02	2.63E-03
S26 20.820 E27 19.114	3.73E-01	9.63E-02	1.01E-01	5.05E-03	6.09E-02	1.92E-02	4.09E-03	2.62E-03			1.01E-01	5.05E-03	5.48E-02	4.38E-03
S26 20.825 E27 19.114	5.80E-01	1.22E-01	2.20E-01	7.22E-03	1.92E-01	2.62E-02	2.66E-02	9.81E-03			2.20E-01	7.22E-03	5.31E-02	4.24E-03
S26 20.830 E27 19.114	4.06E-01	6.01E-02	1.47E-01	5.81E-03	1.55E-01	2.36E-02	1.00E-02	3.21E-03			1.47E-01	5.81E-03		
S26 21.256 E27 18.366	7.29E-01	1.01E-01	2.27E-01	8.56E-03	3.15E-01	3.61E-02	9.87E-03	4.72E-03			2.27E-01	8.56E-03	9.37E-02	6.55E-03
S26 21.256 E27 18.383	4.40E+00	8.12E-01	1.04E+00	2.29E-02	1.46E+00	1.06E-01	2.72E-01	3.92E-02	1.33E-01	3.34E-02	1.04E+00	2.29E-02	1.77E-01	1.09E-02
S26 21.259 E27 18.402	7.89E-01	1.67E-01	2.51E-01	8.26E-03	2.02E-01	3.08E-02	4.40E-02	1.37E-02					4.42E-02	4.19E-03
S26 21.335 E27 18.117	1.58E-01	2.48E-02	9.87E-02	5.42E-03			-1.21E-03	2.06E-03			9.87E-02	5.42E-03	5.29E-02	4.51E-03
S26 21.340 E27 18.117	1.07E+00	2.05E-01	2.73E-01	8.04E-03	3.22E-01	3.35E-02	6.65E-02	1.42E-02			2.73E-01	8.04E-03	7.24E-02	4.79E-03
S26 21.345 E27 18.117	3.35E-01	5.12E-02	2.09E-01	7.53E-03	1.31E-01	2.59E-02	1.39E-03	3.06E-03			2.09E-01	7.53E-03	7.47E-02	5.22E-03
S26 21.420 E27 17.712	4.87E-01	1.23E-01	8.37E-02	4.63E-03	7.39E-02	1.91E-02	2.66E-02	8.75E-03			8.37E-02	4.63E-03	4.99E-02	4.07E-03
S26 21.425 E27 17.712	5.63E-01	7.74E-02	2.08E-01	7.22E-03	1.76E-01	2.67E-02	2.72E-02	1.08E-02			2.08E-01	7.22E-03	7.57E-02	5.08E-03
S26 21.430 E27 17.712	1.44E-01	1.41E-02	9.66E-02	5.29E-03	6.18E-02	2.05E-02	6.16E-03	2.76E-03			9.66E-02	5.29E-03	7.84E-02	5.04E-03
S26 21.738 E27 16.822	3.50E-01	4.76E-02	1.82E-01	7.28E-03	1.43E-01	2.47E-02	2.25E-03	3.38E-03			1.82E-01	7.28E-03	7.17E-02	5.33E-03
S26 21.743 E27 16.822	1.49E-01	2.55E-02	1.43E-01	6.29E-03	5.21E-02	2.07E-02	-9.27E-03	4.08E-04			1.43E-01	6.29E-03	1.03E-01	6.06E-03
S26 21.748 E27 16.822	1.88E-01	2.77E-02	5.30E-02	3.89E-03	4.64E-02	1.88E-02	3.10E-03	2.34E-03			5.30E-02	3.89E-03	6.95E-02	4.83E-03
S26 21.922 E27 15.989	2.75E-01	4.36E-02	1.31E-01	5.51E-03	5.23E-02	1.97E-02	-6.47E-04	2.34E-03			1.31E-01	5.51E-03	9.75E-02	5.56E-03
S26 21.929 E27 15.989	1.68E+00	3.15E-01	2.20E-01	7.62E-03	2.49E-01	3.40E-02	9.01E-02	1.55E-02			2.20E-01	7.62E-03	8.43E-02	5.29E-03
S26 21.937 E27 15.989	2.28E-01	1.89E-02	9.44E-02	5.17E-03	7.28E-02	2.02E-02	2.90E-02	9.80E-03			9.44E-02	5.17E-03	9.86E-02	6.07E-03
S26 22.160 E27 14.523	7.09E-01	6.44E-02	1.55E-01	5.89E-03	1.33E-01	2.44E-02	9.29E-03	2.77E-03	-9.85E-04	2.28E-03	1.55E-01	5.89E-03	8.83E-02	1.90E-03
S26 22.160 E27 14.523	2.50E-01	3.59E-02	7.97E-02	1.56E-03	8.43E-02	6.74E-03	2.89E-02	9.13E-03			7.97E-02	1.56E-03	6.92E-02	4.42E-03
S26 22.170 E27 14.492	7.42E+00	1.12E+00	9.63E-01	2.06E-02	1.67E+00	1.07E-01	5.36E-03	2.26E-03			9.63E-01	2.06E-02	6.48E-02	4.52E-03

Empty spaces indicate a lower limit of determination value was obtained. See the end of the Table to find an indication of the lower limits

GPS Coordinates	U-238		RA-226		PB-210		U-235		AC-227		RA-228		TH-228	
	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 22.170 E27 14.492	5.95E+00	9.16E-01	7.72E-01	1.62E-02	1.13E+00	7.57E-02	3.41E-01	4.49E-02	6.22E-02	2.93E-02	7.72E-01	1.62E-02	1.18E-01	7.63E-03
S26 22.170 E27 14.492	1.87E-01	2.12E-02	6.75E-02	4.07E-03	3.17E-02	1.45E-02	2.92E-01	3.66E-02	6.05E-02	2.10E-02	6.75E-02	4.07E-03		
S26 22.182 E27 14.555	4.65E-01	6.54E-02	1.26E-01	5.45E-03	1.22E-01	2.57E-02	2.16E-02	9.22E-03	1.32E-02	1.05E-02	1.26E-01	5.45E-03	9.46E-02	6.02E-03
S26 22.182 E27 14.555	1.66E+00	3.35E-01	4.52E-01	1.14E-02	4.80E-01	4.91E-02	1.10E-01	1.99E-02	3.94E-02	1.44E-02	4.52E-01	1.14E-02	7.17E-02	4.94E-03
S26 22.189 E27 14.717	5.88E-01	9.14E-02	1.08E-01	1.59E-03	1.19E-01	6.96E-03	2.82E-02	3.26E-03	5.75E-03	2.10E-03	1.08E-01	1.59E-03	3.77E-02	1.01E-03
S26 22.190 E27 14.504	6.24E-01	5.98E-02	3.65E-01	9.39E-03	2.67E-01	3.03E-02	-1.10E-03	7.76E-03			3.65E-01	9.39E-03	5.98E-02	4.53E-03
S26 22.190 E27 14.504	1.41E+00	2.02E-01	3.26E-01	9.09E-03	3.40E-01	3.72E-02	1.03E-02	4.37E-03			3.26E-01	9.09E-03	6.21E-02	4.41E-03
S26 22.190 E27 14.504	4.02E-01	3.92E-02	1.70E-01	6.34E-03	1.70E-01	2.37E-02	7.56E-02	1.55E-02			1.70E-01	6.34E-03	5.86E-02	4.76E-03
S26 22.194 E27 14.449	7.10E-01	9.84E-02	2.13E-01	8.46E-03	1.58E-01	3.32E-02	4.58E-02	6.12E-03			2.13E-01	8.46E-03		
S26 22.194 E27 14.449	4.38E-01	4.57E-02	2.87E-01	1.06E-02			-1.97E-03	4.22E-03			2.87E-01	1.06E-02		
S26 22.194 E27 14.449	1.88E+00	3.34E-01	3.69E-01	9.57E-03	4.39E-01	4.30E-02	3.54E-02	1.37E-02	5.34E-03	6.32E-03	3.69E-01	9.57E-03		
S26 22.197 E27 14.867	1.33E+00	2.09E-01	3.86E-01	1.07E-02	3.46E-01	4.11E-02	2.93E-02	5.81E-03			3.86E-01	1.07E-02	7.18E-02	5.40E-03
S26 22.198 E27 14.721	1.13E+00	2.15E-01	2.02E-01	6.73E-03	1.24E-01	2.77E-02	4.87E-02	1.28E-02			2.02E-01	6.73E-03	6.54E-02	4.69E-03
S26 22.203 E27 14.459	1.15E+00	1.16E-01	3.55E-01	4.01E-03	3.97E-01	1.71E-02	6.30E-02	6.24E-03			3.55E-01	4.01E-03	1.56E-01	8.60E-03
S26 22.203 E27 14.459	7.00E+00	9.72E-01	1.03E+00	1.91E-02	1.25E+00	8.59E-02	3.08E-01	3.79E-02	7.28E-02	2.73E-02	1.03E+00	1.91E-02		
S26 22.205 E27 14.867	7.58E-01	1.07E-01	2.44E-01	8.40E-03	1.24E-01	2.92E-02	3.17E-02	1.34E-02			2.44E-01	8.40E-03	7.40E-02	5.37E-03
S26 22.206 E27 14.721	7.11E-01	9.62E-02	1.88E-01	7.22E-03	1.89E-01	2.87E-02	3.43E-02	1.22E-02			1.88E-01	7.22E-03	7.58E-02	5.51E-03
S26 22.213 E27 14.867	5.66E-01	1.09E-01	1.26E-01	5.54E-03	4.61E-02	2.25E-02	7.22E-03	3.11E-03			1.26E-01	5.54E-03	6.04E-02	4.45E-03
S26 22.214 E27 14.721	2.82E-01	2.88E-02	1.35E-01	5.21E-03	6.56E-02	2.08E-02	2.18E-03	2.66E-03			1.35E-01	5.21E-03	6.42E-02	4.29E-03
S26 22.240 E27 14.404	4.44E-01	6.38E-02	1.21E-01	7.04E-03	7.75E-02	2.59E-02	1.24E-02	3.81E-03			1.21E-01	7.04E-03		
S26 22.240 E27 14.404	7.42E-01	8.39E-02	1.77E-01	8.51E-03	2.41E-01	3.49E-02	8.94E-03	4.38E-03			1.77E-01	8.51E-03		
S26 22.240 E27 15.160	3.15E+00	5.28E-01	7.08E-01	1.56E-02	7.82E-01	6.66E-02	1.87E-01	2.99E-02	1.37E-01	2.29E-02	7.08E-01	1.56E-02	1.20E-01	7.57E-03
S26 22.244 E27 14.424	1.04E+00	9.44E-02	2.31E-01	8.25E-03	2.03E-01	3.40E-02	3.99E-02	1.22E-02			2.31E-01	8.25E-03		
S26 22.244 E27 14.424	6.94E-01	1.61E-01	1.48E-01	6.30E-03	1.37E-01	3.16E-03	2.06E-02	1.01E+00						
S26 22.245 E27 15.160	3.84E+00	7.11E-01	8.77E-01	1.88E-02	9.74E-01	7.89E-02	2.53E-01	3.49E-02	1.32E-01	1.97E-02	8.77E-01	1.88E-02	1.40E-01	9.09E-03
S26 22.250 E27 15.160	3.35E+00	6.98E-01	9.22E-01	2.16E-02	1.29E+00	9.94E-02	2.48E-01	3.77E-02	1.83E-01	3.32E-02	9.22E-01	2.16E-02	1.76E-01	1.04E-02
S26 22.267 E27 14.318	8.40E-02	1.87E-02	4.08E-02	3.23E-03	5.92E-02	1.37E-02	2.13E-03	1.78E-03			4.08E-02	3.23E-03	5.20E-02	3.86E-03
S26 22.267 E27 14.318	2.11E-01	3.14E-02	4.89E-02	3.77E-03	6.05E-02	1.91E-02	-3.17E-03	2.44E-04			1.05E-01	1.57E-02	4.63E-02	4.22E-03
S26 22.267 E27 14.318	7.98E-01	1.09E-01	1.17E-01	5.43E-03	9.58E-02	2.62E-02	3.46E-02	1.03E-02			1.17E-01	5.43E-03	5.96E-02	4.43E-03
S26 22.267 E27 14.318	6.35E-01	1.46E-01	1.72E-01	6.85E-03	1.92E-01	2.75E-02	3.10E-02	1.10E-02			1.72E-01	6.85E-03	1.07E-01	6.11E-03
S26 22.267 E27 14.318	2.28E+00	3.97E-01	3.39E-01	9.63E-03	4.32E-01	4.40E-02	1.17E-01	1.94E-02	4.15E-02	1.44E-02	3.39E-01	9.63E-03	9.60E-02	5.82E-03
S26 22.282 E27 14.366	7.47E-01	1.03E-01	1.59E-01	5.94E-03	1.50E-01	2.52E-02	2.43E-02	9.85E-03			1.59E-01	5.94E-03		
S26 22.282 E27 14.366	2.87E-01	6.60E-02	1.26E-01	6.77E-03	1.40E-01	3.02E-02	-8.19E-03	4.39E-04			1.26E-01	6.77E-03		
S26 22.293 E27 14.392	9.00E-01	1.98E-01	1.94E-01	7.41E-03	1.69E-01	3.18E-02	4.16E-02	1.46E-02			1.94E-01	7.41E-03		
S26 22.293 E27 14.392	1.02E+00	2.23E-01	2.24E-01	8.78E-03	1.98E-01	3.80E-02	5.17E-02	1.33E-02			2.24E-01	8.78E-03		

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GPS Coordinates	U-238		RA-226		PB-210		U-235		AC-227		RA-228		TH-228	
	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 22.308 E27 14.283	5.08E-01	7.87E-02	8.02E-02	4.85E-03	5.93E-02	1.82E-02	2.30E-02	1.01E-02			8.02E-02	4.85E-03		
S26 22.308 E27 14.283	5.80E-01	5.46E-02	9.54E-02	5.47E-03	5.36E-02	2.04E-02	3.12E-02	1.05E-02			9.54E-02	5.47E-03	4.38E-02	3.77E-03
S26 22.308 E27 14.283	3.31E-01	4.86E-02	1.04E-01	4.88E-03	1.07E-01	2.05E-02	6.53E-03	2.94E-03			1.04E-01	4.88E-03		
S26 22.320 E27 14.327	2.37E-01	3.82E-02	1.67E-01	7.17E-03	1.15E-01	2.25E-02	-9.35E-03	3.93E-04			1.67E-01	7.17E-03		
S26 22.320 E27 14.327	1.66E-01	2.66E-02	1.44E-01	6.06E-03	5.70E-02	2.08E-02	-2.93E-03	2.70E-03						
S26 22.320 E27 14.327	4.65E-01	6.56E-02	2.04E-01	7.74E-03	8.26E-02	2.75E-02	2.89E-03	3.55E-03			2.04E-01	7.74E-03		
S26 22.327 E27 14.356	1.29E+00	2.55E-01	4.05E-01	1.09E-02	2.41E-01	4.03E-02	2.13E-02	5.76E-03			4.05E-01	1.09E-02	8.64E-02	5.88E-03
S26 22.330 E27 14.301	4.15E-01	5.82E-02	1.16E-01	5.61E-03	6.34E-02	2.67E-02	2.89E-02	4.39E-03			1.16E-01	5.61E-03	7.72E-02	4.97E-03
S26 22.330 E27 14.301	3.69E-02	1.00E-02	4.65E-02	3.40E-03	4.82E-02	1.32E-02	3.50E-02	1.02E-02			1.78E-03	4.84E-04	5.56E-02	4.57E-03
S26 22.330 E27 14.301	1.38E+00	2.27E-01	2.76E-01	7.95E-03	2.08E-01	2.97E-02	-7.84E-04	2.20E-03			2.76E-01	7.95E-03	6.73E-02	4.32E-03
S26 22.330 E27 14.301	8.03E-01	1.10E-01	6.07E-02	4.07E-03	9.31E-02	2.15E-02	8.00E-04	2.48E-03			6.07E-02	4.07E-03	5.72E-02	4.22E-03
S26 22.330 E27 14.301	2.08E-01	3.25E-02	1.07E-01	5.35E-03	6.11E-02	2.13E-02	8.04E-03	7.94E-03			1.07E-01	5.35E-03	5.48E-02	4.09E-03
S26 22.330 E27 14.301	2.46E-01	3.29E-02	7.95E-02	4.31E-03	9.29E-02	1.96E-02	-4.17E-03	2.45E-04			7.95E-02	4.31E-03	6.98E-02	5.07E-03
S26 22.330 E27 14.301	1.84E-01	3.03E-02	7.07E-02	4.43E-03	4.10E-02	1.99E-02	8.11E-04	1.54E-03			7.07E-02	4.43E-03	7.72E-02	4.73E-03
S26 22.330 E27 14.301	6.97E-02	1.46E-02	4.65E-02	3.41E-03	4.27E-02	1.53E-02	-4.51E-03	2.85E-04			4.65E-02	3.41E-03	5.96E-02	4.59E-03
S26 22.330 E27 14.301	1.70E-01	2.70E-02	6.44E-02	3.77E-03	5.92E-02	1.76E-02	-3.01E-03	2.20E-04			6.44E-02	3.77E-03	6.18E-02	4.39E-03
S26 22.330 E27 14.301	1.13E+00	2.29E-01	1.54E-01	6.60E-03	1.45E-01	2.90E-02	6.39E-02	1.35E-02			1.54E-01	6.60E-03	5.75E-02	4.51E-03
S26 22.330 E27 14.301	1.77E-01	2.68E-02	9.23E-02	5.57E-03	7.05E-02	1.87E-02	4.84E-03	8.81E-03			9.23E-02	5.57E-03	7.67E-02	5.21E-03
S26 22.330 E27 14.301	1.34E-01	2.57E-02	6.96E-02	4.39E-03	9.37E-02	2.06E-02	6.39E-03	2.54E-03	8.53E-03	4.88E-03	6.96E-02	4.39E-03	4.46E-02	3.52E-03
S26 22.338 E27 14.223	4.48E+00	5.33E-01	6.58E-01	1.36E-02	8.49E-01	6.19E-02	1.34E-02	4.08E-03			6.58E-01	1.36E-02		
S26 22.338 E27 14.223	6.36E-01	1.40E-01	2.97E-01	8.06E-03	1.98E-01	2.77E-02	2.52E-01	3.13E-02	4.00E-02	2.08E-02	2.97E-01	8.06E-03	9.96E-02	6.27E-03
S26 22.346 E27 14.251	7.70E-01	7.07E-02	2.01E-01	6.85E-03	1.67E-01	2.53E-02	4.71E-03	3.20E-03			2.01E-01	6.85E-03		
S26 22.346 E27 14.251	2.07E-01	3.07E-02	9.32E-02	4.93E-03	4.47E-02	1.93E-02	-6.04E-03	3.19E-04			9.32E-02	4.93E-03		
S26 22.346 E27 14.251	3.34E-01	5.02E-02	1.29E-01	6.19E-03	6.13E-02	2.28E-02	1.41E-02	3.78E-03			1.29E-01	6.19E-03	6.03E-02	4.47E-03
S26 22.358 E27 14.293	7.86E-01	1.10E-01	1.96E-01	7.46E-03	2.10E-01	3.25E-02	-5.53E-03	3.05E-04			1.96E-01	7.46E-03		
S26 22.358 E27 14.293	2.02E-01	3.22E-02	8.53E-02	4.71E-03	8.44E-02	1.80E-02	4.05E-02	1.27E-02			8.53E-02	4.71E-03		
S26 22.365 E27 14.233	1.40E-01	2.20E-02	6.38E-02	3.97E-03	2.77E-02	1.70E-02	5.77E-03	6.67E-03			6.38E-02	3.97E-03		
S26 22.365 E27 14.233	6.24E-01	1.22E-01	1.42E-01	5.07E-03	1.02E-01	1.96E-02	1.76E-02	1.02E-02			1.42E-01	5.07E-03	3.22E-02	2.97E-03
S26 22.365 E27 14.233	1.89E-01	4.68E-02	9.96E-02	5.77E-03	8.63E-02	2.07E-02	2.67E-02	8.54E-03			9.96E-02	5.77E-03		
S26 22.367 E27 14.317	1.08E+00	1.97E-01	2.69E-01	7.99E-03	1.75E-01	3.05E-02	5.56E-02	1.33E-02					4.84E-02	4.21E-03
S26 22.378 E27 14.263	1.01E+00	2.24E-01	1.80E-01	7.14E-03	2.21E-01	3.38E-02	5.06E-02	1.38E-02			1.80E-01	7.14E-03	8.68E-02	5.82E-03
S26 22.387 E27 14.285	7.59E-01	1.03E-01	1.82E-01	7.32E-03	2.42E-01	3.12E-02	3.59E-02	1.19E-02			1.82E-01	7.32E-03		
S26 22.613 E27 13.708	2.02E+00	2.22E-01	2.72E-01	7.50E-03	2.81E-01	3.35E-02	8.66E-02	1.46E-02	1.03E-02	1.71E-02	2.72E-01	7.50E-03	4.79E-02	3.79E-03
S26 22.646 E27 13.706	1.16E+00	2.34E-01	2.92E-01	8.37E-03	3.11E-01	3.66E-02	7.03E-02	1.33E-02	1.63E-02	1.16E-02	2.92E-01	8.37E-03	6.55E-02	4.54E-03
S26 22.655 E27 13.686	1.72E+00	3.60E-01	4.82E-01	1.36E-02	6.24E-01	6.05E-02	3.41E-02	1.11E-02			4.82E-01	1.36E-02	8.86E-02	5.56E-03

Empty spaces indicate a lower limit of determination value was obtained. See the end of the Table to find an indication of the lower limits

GPS Coordinates	U-238		RA-226		PB-210		U-235		AC-227		RA-228		TH-228	
	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity		Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 22.655 E27 13.686	8.22E-01	1.30E-01	1.73E-01	6.39E-03	1.45E-01	2.74E-02	3.97E-02	6.26E-03			1.73E-01	6.39E-03	1.22E-01	7.93E-03
S26 22.660 E27 13.650	3.03E+00	5.18E-01	6.61E-01	1.41E-02	7.56E-01	5.66E-02	1.47E-01	2.50E-02			6.61E-01	1.41E-02	9.00E-02	6.01E-03
S26 22.699 E27 13.585	1.65E+00	3.10E-01	3.40E-01	9.05E-03	2.98E-01	3.62E-02	7.96E-02	1.50E-02			3.40E-01	9.05E-03	7.38E-02	4.96E-03
S26 22.699 E27 13.650	2.83E+00	4.07E-01	6.64E-01	1.53E-02	6.12E-01	5.76E-02	1.37E-01	1.96E-02	8.52E-01	1.04E-01			2.13E-01	5.22E-02
S26 22.722 E27 13.538	1.55E+00	2.89E-01	2.66E-01	8.56E-03	2.59E-01	3.62E-02	7.50E-02	1.40E-02	3.68E-01	5.40E-02	2.66E-01	8.56E-03	4.03E-02	4.14E-03
S26 22.725 E27 13.594	4.03E+00	7.23E-01	8.58E-01	1.80E-02	7.72E-01	7.17E-02	1.95E-01	3.49E-02			8.58E-01	1.80E-02	8.65E-02	7.36E-03
S26 22.744 E27 13.538	1.29E+00	1.14E-01	2.51E-01	8.28E-03	1.60E-01	3.08E-02	6.24E-02	5.52E-03			2.51E-01	8.28E-03	5.20E-02	4.44E-03
S26 22.778 E27 13.486	2.26E+00	4.15E-01	4.80E-01	1.21E-02	5.07E-01	5.26E-02	1.09E-01	2.01E-02	2.62E-02	1.07E-02	4.80E-01	1.21E-02	7.64E-02	5.80E-03
S26 22.778 E27 13.546	1.85E+00	2.48E-01	2.97E-01	9.20E-03	1.72E-01	3.58E-02	8.92E-02	1.20E-02			2.97E-01	9.20E-03	5.84E-02	4.77E-03
S26 22.805 E27 13.538	1.37E+00	2.24E-01	1.82E-01	7.49E-03	1.93E-01	3.39E-02	6.63E-02	1.08E-02			1.82E-01	7.49E-03	9.10E-02	6.22E-03
S26 22.814 E27 13.446	3.12E+00	5.59E-01	5.68E-01	1.44E-02	6.07E-01	6.22E-02	1.51E-01	2.70E-02	9.23E-01	1.10E-01	5.68E-01	1.44E-02	1.00E-01	7.26E-03
S26 22.814 E27 13.490	1.88E+00	3.50E-01	2.55E-01	8.78E-03	2.75E-01	3.88E-02	9.10E-02	1.69E-02			2.55E-01	8.78E-03	8.55E-02	5.92E-03
S26 22.831 E27 13.489	1.74E+00	2.61E-01	1.94E-01	6.14E-03	1.64E-01	2.77E-02	8.40E-02	1.26E-02			1.94E-01	6.14E-03	5.31E-02	3.88E-03
S26 22.831 E27 13.540	3.63E+00	4.33E-01	4.04E-01	1.00E-02	4.48E-01	4.23E-02	1.75E-01	2.09E-02			4.04E-01	1.00E-02	7.91E-02	1.51E-03
S26 22.831 E27 13.540	1.33E+00	1.32E-01	4.85E-02	1.06E-03	6.17E-02	6.44E-03	6.43E-02	6.38E-03			4.85E-02	1.06E-03	6.82E-02	5.29E-03
S26 22.853 E27 13.429	1.45E+00	2.68E-01	4.57E-01	1.31E-02	5.86E-01	5.64E-02	7.01E-02	1.30E-02	2.90E-01	6.23E-02	4.57E-01	1.31E-02	1.16E-01	7.73E-03
S26 22.859 E27 13.490	1.90E+00	4.04E-01	4.55E-01	1.13E-02	3.87E-01	4.41E-02	9.20E-02	1.95E-02			4.55E-01	1.13E-02	8.17E-02	5.75E-03
S26 22.859 E27 13.523	2.51E+00	4.03E-01	6.44E-01	1.58E-02	7.23E-01	6.32E-02	1.21E-01	1.94E-02	7.09E-01	9.34E-02	6.44E-01	1.58E-02	1.11E-01	7.68E-03
S26 22.871 E27 13.430	1.55E+00	3.12E-01	3.21E-01	7.94E-03	2.94E-01	3.44E-02	7.50E-02	1.51E-02			3.21E-01	7.94E-03	5.72E-02	4.00E-03
S26 22.871 E27 13.430	4.35E-01	4.15E-02	1.58E-01	5.59E-03	1.16E-01	2.00E-02	2.10E-02	2.00E-03	2.66E-03	3.94E-03	1.58E-01	5.59E-03	5.58E-02	3.97E-03
S26 22.877 E27 13.429	2.84E+00	5.33E-01	6.02E-01	1.40E-02	7.39E-01	6.34E-02	1.37E-01	2.58E-02	4.84E-01	5.62E-02	6.02E-01	1.40E-02	1.16E-01	7.34E-03
S26 22.882 E27 13.490	7.87E-01	1.83E-01	4.50E-01	1.20E-02	1.61E-01	3.52E-02	3.80E-02	8.84E-03			4.50E-01	1.20E-02	8.02E-02	5.88E-03
S26 22.902 E27 13.156	5.29E-01	7.23E-02	1.74E-01	6.54E-03	1.88E-01	2.61E-02	2.55E-02	3.49E-03			1.74E-01	6.54E-03	5.97E-02	4.70E-03
S26 22.934 E27 13.156	6.83E-01	9.41E-02	1.59E-01	6.91E-03	1.36E-01	2.93E-02	3.30E-02	4.55E-03			1.59E-01	6.91E-03	9.31E-02	6.08E-03
S26 22.938 E27 13.127	8.91E-01	1.25E-01	3.42E-01	9.22E-03	3.92E-01	3.71E-02	4.30E-02	6.05E-03			3.42E-01	9.22E-03	4.58E-02	4.11E-03
S26 22.938 E27 13.127	1.05E+00	2.33E-01	2.73E-01	8.94E-03	2.64E-01	3.68E-02	5.06E-02	1.13E-02			2.73E-01	8.94E-03	8.66E-02	5.96E-03
S26 22.938 E27 13.127	1.56E+00	2.37E-01	3.99E-01	1.14E-02	5.35E-01	4.82E-02	7.54E-02	1.14E-02	1.20E-02	7.43E-03	3.99E-01	1.14E-02	7.10E-02	5.51E-03
S26 22.944 E27 13.105	3.72E-01	5.26E-02	2.29E-01	8.12E-03	1.33E-01	3.01E-02	1.80E-02	2.54E-03			2.29E-01	8.12E-03	7.44E-02	5.63E-03
S26 22.964 E27 13.106	1.81E+00	2.58E-01	5.18E-01	1.31E-02	6.34E-01	5.21E-02	8.76E-02	1.25E-02	5.21E-02	1.49E-02	5.18E-01	1.31E-02	1.03E-01	6.73E-03
S26 22.982 E27 12.976	2.21E+00	3.28E-01	4.91E-01	1.23E-02	4.47E-01	4.72E-02	1.07E-01	1.59E-02			4.91E-01	1.23E-02	7.80E-02	5.96E-03
S26 22.982 E27 13.041	1.76E+00	3.59E-01	4.33E-01	1.00E-02	4.46E-01	4.17E-02	8.48E-02	1.74E-02			4.33E-01	1.00E-02	7.97E-02	5.02E-03
S26 22.985 E27 12.924	9.23E-01	2.15E-01	3.39E-01	9.70E-03	2.12E-01	3.49E-02	4.46E-02	1.04E-02					4.43E-02	3.69E-03
S26 22.994 E27 13.106	4.68E-01	4.69E-02	2.52E-01	8.78E-03	9.95E-02	3.12E-02	2.26E-02	2.27E-03			2.52E-01	8.78E-03	8.43E-02	5.93E-03
S26 23.014 E27 12.976	6.36E-01	5.67E-02	1.87E-01	2.14E-03	1.96E-01	8.77E-03	3.07E-02	2.74E-03	8.24E-03	2.44E-03	1.87E-01	2.14E-03	4.80E-02	1.04E-03
S26 23.016 E27 12.924	1.20E+00	2.54E-01	4.00E-01	1.13E-02	4.68E-01	4.72E-02	5.78E-02	1.23E-02			4.00E-01	1.13E-02	9.04E-02	6.41E-03

Empty spaces indicate a lower limit of determination value was obtained. See the end of the Table to find an indication of the lower limits

GPS Coordinates	U-238		RA-226		PB-210		U-235		AC-227		RA-228		TH-228	
	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity		Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 23.019 E27 13.040	3.47E-01	6.45E-02	1.11E-01	1.97E-03	1.03E-01	8.06E-03	1.68E-02	3.12E-03	2.08E-03	3.10E-03	1.11E-01	1.97E-03	5.24E-02	1.54E-03
S26 23.044 E27 12.856	2.28E+00	2.91E-01	4.76E-01	1.21E-02	6.19E-01	5.08E-02	1.10E-01	1.40E-02			4.76E-01	1.21E-02	7.05E-02	5.62E-03
S26 23.075 E27 12.856	8.89E-01	1.85E-01	3.87E-01	9.70E-03	3.59E-01	3.67E-02	4.29E-02	8.94E-03			3.87E-01	9.70E-03	8.89E-02	5.73E-03
S26 23.098 E27 12.785	4.27E-01	6.13E-02	1.74E-01	6.60E-03	1.18E-01	2.33E-02	2.06E-02	2.96E-03			1.74E-01	6.60E-03	6.13E-02	4.64E-03
S26 23.098 E27 12.856	2.11E+00	3.93E-01	3.07E-01	1.05E-02	2.43E-01	4.33E-02	1.02E-01	1.90E-02			3.07E-01	1.05E-02	5.98E-02	5.65E-03
S26 23.098 E27 12.856	3.80E-01	5.52E-02	7.45E-02	4.11E-03	1.23E-01	1.97E-02	1.83E-02	2.66E-03			7.45E-02	4.11E-03	6.17E-02	4.26E-03
S26 23.119 E27 12.785	9.93E-01	1.09E-01	3.33E-01	4.06E-03	3.76E-01	1.74E-02	4.80E-02	5.27E-03	1.14E-02	3.92E-03	3.33E-01	4.06E-03	6.43E-02	1.45E-02
Average	9.34E-01		2.60E-01		2.71E-01		4.00E-02		1.07E-01		2.48E-01		7.47E-02	
Standard deviation	1.05E+00		2.39E-01		2.96E-01		5.09E-02		2.05E-01		2.31E-01		3.17E-02	
Maximum	7.42E+00		1.23E+00		1.67E+00		3.39E-01		9.23E-01		1.23E+00		2.17E-01	
Minimum	3.69E-02		1.91E-02		2.77E-02		-6.38E-02		-1.53E-03		1.78E-03		1.64E-02	
Median	6.30E-01		1.81E-01		1.61E-01		3.07E-02		3.64E-02		1.73E-01		7.06E-02	

Empty spaces indicate a lower limit of determination value was obtained. See the end of the Table to find an indication of the lower limits

Appendix 2 The data base for ^{40}K, ^{134}Cs and ^{137}Cs gamma spectrometric and measured and calculated gross alpha-beta results

									Calculated alpha and beta				Measured alpha and beta			
	K-40		Cs-134			Cs-137			alpha		beta		alpha		beta	
GPS Coordinates	Activity	Uncertainty	Activity	Uncertainty	MDA	Activity	Uncertainty	MDA	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 19.038 E27 23.395	9.86E-02	2.13E-02			2.69E-02			5.24E-03	2.11E+00	6.21E-03	2.10E+00	2.19E-02	1.46E+00	3.86E-01	3.82E-01	6.29E-02
S26 19.039 E27 23.302	3.99E-01	5.32E-02			1.07E-01			1.83E-02	1.23E+01	3.75E-01	1.22E+01	3.84E-01	1.20E+01	8.47E-01	6.10E+00	1.53E-01
S26 19.039 E27 23.302	3.85E-01	6.44E-02			1.19E-01			1.91E-02	9.85E+00	6.32E-01	9.98E+00	6.38E-01	9.89E+00	7.64E-01	7.72E+00	1.81E-01
S26 19.039 E27 23.337	9.12E-02	2.04E-02			4.33E-02			7.11E-03	1.38E+00	4.33E-02	1.30E+00	4.97E-02	1.29E+00	3.72E-01	8.17E-01	7.74E-02
S26 19.039 E27 23.337	1.95E-01	4.88E-02			1.34E-01			2.01E-02	8.40E+00	5.63E-01	8.17E+00	5.68E-01	7.98E+00	6.88E-01	5.88E+00	1.60E-01
S26 19.039 E27 23.365	1.11E-01	2.13E-02			4.84E-02			7.12E-03	2.38E+00	1.34E-01	2.39E+00	1.37E-01	1.98E+00	4.18E-01	1.56E+00	9.28E-02
S26 19.039 E27 23.365	2.69E-01	3.69E-02			7.52E-02			1.20E-02	5.90E+00	2.78E-01	5.68E+00	2.82E-01	6.33E+00	6.17E-01	4.35E+00	1.41E-01
S26 19.042 E27 23.428	4.04E-02	1.67E-02			4.52E-02			7.05E-03	5.04E+00	1.98E-01	4.68E+00	1.81E-01	8.58E-01	2.61E-01	5.88E-01	7.26E-02
S26 19.042 E27 23.428	7.80E-02	2.84E-02			8.02E-02			1.42E-02	1.24E+00	4.84E-02	1.17E+00	5.78E-02	6.08E+00	6.30E-01	3.05E+00	1.15E-01
S26 19.042 E27 23.428	7.59E-02	2.42E-02			6.44E-02			1.02E-02	3.49E+00	9.03E-02	3.38E+00	9.71E-02	3.17E+00	5.06E-01	1.95E+00	9.22E-02
S26 19.055 E27 23.411	3.38E-01	5.92E-02			1.04E-01			1.79E-02	1.46E+00	6.32E-02	1.50E+00	8.54E-02	6.00E+00	6.24E-01	4.41E+00	1.35E-01
S26 19.055 E27 23.411	1.44E-01	3.03E-02			5.48E-02			7.38E-03	2.09E+00	8.35E-02	2.02E+00	9.22E-02	1.24E+00	3.70E-01	5.62E-01	7.05E-02
S26 19.055 E27 23.411	5.51E-02	2.42E-02			5.19E-02			7.82E-03	1.71E+00	8.65E-02	1.64E+00	9.21E-02	1.77E+00	4.05E-01	1.24E+00	8.64E-02
S26 19.055 E27 23.411	1.24E-01	2.78E-02			5.67E-02			8.47E-03	1.96E+00	9.56E-02	1.88E+00	1.05E-01	2.10E+00	4.28E-01	1.02E+00	8.07E-02
S26 19.055 E27 23.411	1.66E-01	3.08E-02			5.53E-02			1.04E-02	1.37E+00	8.62E-02	1.57E+00	9.40E-02	1.76E+00	4.04E-01	1.41E+00	9.00E-02
S26 19.055 E27 23.411	2.15E-01	4.04E-02			6.43E-02			1.03E-02	6.67E+00	2.22E-01	6.55E+00	2.31E-01	5.80E+00	6.18E-01	3.39E+00	1.21E-01
S26 19.055 E27 23.411	2.16E-01	3.30E-02			6.43E-02			1.07E-02	3.43E+00	9.37E-02	3.47E+00	1.04E-01	3.98E+00	5.32E-01	2.21E+00	1.04E-01
S26 19.055 E27 23.411	1.07E-01	2.89E-02			6.71E-02			8.31E-03	3.24E+00	1.46E-01	3.20E+00	1.52E-01	3.76E+00	5.37E-01	2.20E+00	9.77E-02
S26 19.056 E27 23.456	1.11E-01	2.41E-02			4.18E-02			6.53E-03	1.18E+00	5.68E-02	1.13E+00	6.35E-02	2.42E+00	4.66E-01	1.20E+00	7.67E-02
S26 19.056 E27 23.456	1.03E-01	2.71E-02			5.25E-02			7.09E-03	5.38E-01	2.59E-02	4.71E-01	3.68E-02	7.50E-01	3.55E-01	5.30E-01	6.16E-02
S26 19.057 E27 23.429					3.53E-02			5.46E-03	7.48E-01	5.01E-02	6.97E-01	5.16E-02	5.92E-01	3.19E-01	2.16E-01	6.35E-02
S26 19.057 E27 23.429	8.28E-02	1.88E-02			3.64E-02			4.91E-03	3.90E-01	3.13E-02	4.49E-01	3.60E-02	9.13E-01	3.44E-01	5.56E-01	7.14E-02
S26 19.062 E27 23.282	1.41E-01	2.93E-02			5.26E-02			8.21E-03	5.68E+00	3.63E-01	5.56E+00	3.67E-01	1.88E+00	4.10E-01	9.58E-01	7.96E-02
S26 19.062 E27 23.282	2.15E-01	4.08E-02			1.51E-02			9.13E-03	1.28E+00	6.28E-02	1.29E+00	7.57E-02	5.61E+00	6.20E-01	4.67E+00	1.34E-01
S26 19.062 E27 23.336	2.35E-01	4.65E-02			9.09E-02			1.47E-02	1.12E+01	4.92E-01	1.09E+01	4.98E-01	1.02E+01	7.86E-01	4.81E+00	1.38E-01
S26 19.062 E27 23.336	3.25E-01	5.95E-02			1.22E-01			2.15E-02	8.14E+00	4.85E-01	7.25E+00	4.89E-01	9.53E+00	7.72E-01	6.75E+00	1.57E-01
S26 19.062 E27 23.336	4.13E-01	6.45E-02			1.21E-01			2.02E-02	7.97E+00	2.11E-01	8.12E+00	2.26E-01	9.83E+00	7.59E-01	6.23E+00	1.66E-01
S26 19.063 E27 23.456	1.63E-01	3.48E-02			7.73E-02			1.19E-02	2.55E+00	2.22E-01	2.53E+00	2.26E-01	6.44E+00	6.58E-01	4.31E+00	1.29E-01
S26 19.063 E27 23.456	1.18E-01	2.64E-02			5.05E-02			7.94E-03	5.06E+00	3.80E-01	4.89E+00	3.82E-01	2.68E+00	4.79E-01	1.97E+00	9.32E-02
S26 19.064 E27 23.308	2.47E-01	1.71E-02			3.46E-02			5.19E-03	1.27E+01	5.91E-01	1.28E+01	5.93E-01	1.01E+01	8.87E-01	8.66E+00	1.76E-01
S26 19.064 E27 23.308	3.29E-01	6.36E-02			1.39E-01			2.20E-02	9.96E+00	5.99E-01	9.79E+00	6.05E-01	7.74E+00	6.80E-01	6.68E+00	1.69E-01

Empty spaces indicate a lower limit of determination value was obtained. See the end of the Table to find an indication of the lower limits

	K-40		Cs-134			Cs-137			Calculated alpha and beta				Measured alpha and beta			
									alpha		beta		alpha		beta	
GPS Coordinates	Activity	Uncertainty	Activity	Uncertainty	MDA	Activity	Uncertainty	MDA	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 19.064 E27 23.400	1.02E-01	3.04E-02			7.36E-02			9.57E-03	4.89E-01	3.32E-02	5.45E-01	4.44E-02	3.88E+00	5.27E-01	1.95E+00	9.80E-02
S26 19.064 E27 23.400	1.49E-01	2.61E-02			4.52E-02			6.33E-03	2.23E+00	8.56E-02	2.37E+00	9.35E-02	9.68E-01	3.49E-01	4.93E-01	6.91E-02
S26 19.064 E27 23.429	2.22E-01	3.62E-02			7.24E-02			1.28E-02	7.37E-01	3.61E-02	7.74E-01	4.97E-02	2.47E+00	4.49E-01	1.66E+00	9.41E-02
S26 19.064 E27 23.429	1.16E-01	2.05E-02			3.19E-02			5.46E-03	2.17E+00	9.38E-02	2.24E+00	1.00E-01	1.18E+00	3.64E-01	7.25E-01	7.53E-02
S26 19.064 E27 23.429	2.06E-01	3.13E-02			5.58E-02			8.50E-03	2.27E+00	7.46E-02	2.46E+00	8.46E-02	2.20E+00	4.32E-01	1.45E+00	9.02E-02
S26 19.065 E27 23.345					4.15E-02			5.42E-03	2.90E+00	1.10E-01	2.73E+00	1.13E-01	7.54E-01	2.46E-01	3.59E-01	6.57E-02
S26 19.065 E27 23.345	7.15E-02	2.48E-02			5.91E-02			9.85E-03	1.02E+00	7.80E-02	8.33E-01	6.90E-02	4.15E+00	5.57E-01	2.10E+00	9.44E-02
S26 19.070 E27 23.445	1.08E-01	2.33E-02			2.91E-02			6.99E-03	8.08E+00	2.82E-01	8.20E+00	2.89E-01	2.32E+00	4.42E-01	9.48E-01	7.84E-02
S26 19.070 E27 23.445	6.57E-02	1.98E-02			4.38E-02			7.20E-03	7.75E-01	4.68E-02	8.32E-01	4.92E-02	1.45E+00	3.83E-01	1.03E+00	8.24E-02
S26 19.070 E27 23.445	4.69E-01	6.27E-02			1.11E-01			1.76E-02	4.22E+00	1.56E-01	4.36E+00	1.69E-01	9.36E+00	7.57E-01	5.10E+00	1.42E-01
S26 19.070 E27 23.445	1.61E-01	3.10E-02			5.81E-02			9.53E-03	1.99E+00	5.88E-02	2.02E+00	6.78E-02	5.28E+00	5.95E-01	2.40E+00	1.05E-01
S26 19.070 E27 23.456	8.63E-02	3.20E-02			9.35E-02			1.38E-02	5.21E+00	1.27E-01	5.19E+00	1.38E-01	5.37E+00	6.13E-01	2.97E+00	1.09E-01
S26 19.070 E27 23.456	2.52E-01	4.73E-02			1.08E-01			1.71E-02	7.78E+00	3.78E-01	6.50E+00	3.85E-01	1.27E+01	8.77E-01	5.42E+00	1.40E-01
S26 19.087 E27 23.283	6.41E-02	2.20E-02			4.60E-02			7.48E-03	3.11E+00	9.59E-02	2.85E+00	1.01E-01	1.56E+00	3.92E-01	8.20E-01	7.68E-02
S26 19.087 E27 23.283	1.81E-01	3.13E-02			6.38E-02			9.86E-03	1.17E+00	6.61E-02	1.23E+00	7.45E-02	4.15E+00	5.05E-01	1.86E+00	1.02E-01
S26 19.089 E27 23.308	1.03E-01	2.18E-02			5.02E-02			7.09E-03	2.22E+00	8.31E-03	2.18E+00	2.30E-02	1.18E+00	3.12E-01	9.64E-01	7.04E-02
S26 19.089 E27 23.308	1.05E-01	2.40E-02			3.32E-02			5.57E-03	1.18E+00	6.43E-02	1.10E+00	7.04E-02	9.18E-01	3.46E-01	3.61E-01	6.49E-02
S26 19.089 E27 23.336					5.81E-02			8.86E-03	1.35E+00	5.62E-02	1.13E+00	5.94E-02	1.10E+00	2.93E-01	5.99E-01	7.20E-02
S26 19.089 E27 23.336	1.29E-01	3.39E-02			7.76E-02			1.18E-02	4.48E+00	1.72E-01	4.34E+00	1.78E-01	5.65E+00	6.25E-01	3.00E+00	1.09E-01
S26 19.089 E27 23.336	1.75E-01	3.37E-02			5.76E-02			7.75E-03	1.13E+00	4.48E-02	9.38E-01	5.97E-02	6.88E-01	3.47E-01	8.77E-01	7.16E-02
S26 19.090 E27 23.372	7.84E-02	2.67E-02			5.76E-02			9.66E-03	2.35E+00	4.91E-02	2.04E+00	5.86E-02	1.83E+00	4.11E-01	8.26E-01	7.64E-02
S26 19.090 E27 23.372					8.01E-02			1.21E-02	3.84E+00	1.06E-01	3.00E+00	1.11E-01	5.87E+00	6.21E-01	2.65E+00	1.09E-01
S26 19.090 E27 23.372	1.53E-01	3.68E-02			6.75E-02			1.12E-02	4.04E+00	2.44E-01	4.06E+00	2.49E-01	3.54E+00	5.25E-01	2.26E+00	9.77E-02
S26 19.092 E27 23.344	1.02E-01	2.13E-02			4.64E-02			8.62E-03	7.51E+00	4.22E-01	6.45E+00	4.27E-01	2.26E+00	4.38E-01	1.03E+00	8.05E-02
S26 19.092 E27 23.344	5.81E-01	7.01E-02			1.20E-01			1.81E-02	2.29E+00	9.37E-02	2.37E+00	1.15E-01	1.05E+01	7.98E-01	5.24E+00	1.43E-01
S26 19.092 E27 23.344	1.71E-01	2.74E-02			4.53E-02			6.62E-03	7.79E-01	3.84E-02	7.81E-01	4.67E-02	1.29E+00	3.73E-01	6.12E-01	7.17E-02
S26 19.129 E27 23.255	3.50E-01	5.13E-02			1.00E-01			1.79E-02	6.50E+00	1.63E-01	6.64E+00	1.78E-01	9.37E+00	7.69E-01	3.96E+00	1.22E-01
S26 19.130 E27 23.253	1.24E-01	2.75E-02			5.49E-02			8.78E-03	2.34E+00	7.90E-02	2.20E+00	8.64E-02	3.02E+00	4.37E-01	1.45E+00	9.42E-02
S26 19.132 E27 21.622	2.35E-01	3.26E-02			5.02E-02			7.45E-03	1.09E+00	3.64E-02	1.02E+00	5.12E-02	1.40E+00	3.81E-01	6.76E-01	7.32E-02
S26 19.132 E27 21.622	2.43E-01	9.45E-03			1.18E-02	1.61E-03	3.76E-04	1.17E-03	1.57E+00	7.55E-02	1.51E+00	7.64E-02	1.60E+00	3.34E-01	1.39E+00	9.06E-02
S26 19.133 E27 21.596	2.20E-01	6.31E-02			1.64E-01			2.40E-02	3.09E+00	1.21E-01	2.96E+00	1.43E-01	3.71E+00	5.35E-01	2.18E+00	9.62E-02
S26 19.133 E27 21.596	2.27E-01	4.14E-02			7.82E-02			1.17E-02	3.59E+00	1.21E-01	3.04E+00	1.32E-01	4.63E+00	5.31E-01	2.41E+00	1.12E-01
S26 19.133 E27 21.608	2.39E-01	3.57E-02			5.80E-02			9.90E-03	2.87E+00	1.07E-01	2.76E+00	1.15E-01	1.40E+00	4.02E-01	7.96E-01	6.79E-02
S26 19.133 E27 21.608	1.76E-01	3.42E-02			6.69E-02			1.07E-02	9.64E-01	2.92E-02	8.09E-01	4.40E-02	2.74E+00	4.20E-01	1.76E+00	9.88E-02

Empty spaces indicate a lower limit of determination value was obtained. See the end of the Table to find an indication of the lower limits

	K-40		Cs-134			Cs-137			Calculated alpha and beta				Measured alpha and beta			
									alpha		beta		alpha		beta	
GPS Coordinates	Activity	Uncertainty	Activity	Uncertainty	MDA	Activity	Uncertainty	MDA	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 19.991 E27 20.517	1.05E-01	2.50E-02			4.09E-02			5.92E-03	7.84E-01	2.89E-02	7.10E-01	4.08E-02	9.64E-01	3.71E-01	6.46E-01	6.45E-02
S26 20.001 E27 20.480	1.28E-01	2.98E-02			4.95E-02			7.07E-03	1.80E+00	7.07E-02	1.66E+00	7.90E-02	1.83E+00	3.52E-01	1.15E+00	8.70E-02
S26 20.001 E27 20.480	1.09E-01	2.94E-02			7.45E-02			1.06E-02	1.33E+00	4.03E-02	1.09E+00	5.14E-02	1.28E+00	3.79E-01	9.14E-01	7.35E-02
S26 20.089 E27 20.447	1.24E-01	3.21E-02			8.70E-02			1.47E-02	4.04E+00	3.20E-01	3.64E+00	3.23E-01	2.49E+00	4.52E-01	3.06E+00	1.14E-01
S26 20.139 E27 20.390	1.40E-01	2.67E-02			5.35E-02			6.74E-03	5.14E+00	3.43E-01	5.03E+00	3.46E-01	2.26E+00	4.57E-01	1.22E+00	7.76E-02
S26 20.139 E27 20.390	1.81E-01	3.86E-02			7.76E-02			1.37E-02	1.93E+00	7.89E-02	1.99E+00	8.97E-02	4.16E+00	5.44E-01	3.60E+00	1.21E-01
S26 20.140 E27 19.991	1.84E-01	3.14E-02			5.76E-02			8.56E-03	1.50E+00	3.38E-02	1.38E+00	4.94E-02	1.33E+00	3.10E-01	1.60E+00	9.38E-02
S26 20.140 E27 19.991	1.64E-01	3.78E-02			7.72E-02			1.34E-02	6.72E+00	4.00E-01	6.58E+00	4.04E-01	4.82E+00	5.48E-01	5.83E+00	1.57E-01
S26 20.140 E27 20.485	1.10E-01	2.09E-02			4.51E-02			5.83E-03	1.30E+00	9.44E-02	1.31E+00	9.76E-02	1.06E+00	3.76E-01	1.12E+00	7.71E-02
S26 20.140 E27 20.485	1.28E-01	2.66E-02			4.02E-02			6.72E-03	1.26E+00	7.42E-02	1.26E+00	7.98E-02	1.88E+00	4.33E-01	1.04E+00	7.34E-02
S26 20.140 E27 20.485	9.72E-02	2.06E-02			4.28E-02			5.63E-03	7.84E-01	4.33E-02	7.63E-01	4.91E-02	9.67E-01	3.72E-01	5.57E-01	6.18E-02
S26 20.143 E27 20.110	1.74E-01	2.99E-02			4.52E-02			6.46E-03	5.20E+00	3.49E-01	5.03E+00	3.52E-01	1.13E+00	3.83E-01	6.86E-01	6.53E-02
S26 20.143 E27 20.110	1.07E-01	3.62E-02			8.67E-02			1.46E-02	2.56E+00	1.93E-02	2.48E+00	4.35E-02	4.39E+00	5.56E-01	3.13E+00	1.13E-01
S26 20.145 E27 19.870	1.75E-01	2.76E-02			5.12E-02			7.55E-03	4.52E+00	3.67E-01	4.51E+00	3.70E-01	1.06E+00	3.75E-01	1.27E+00	8.06E-02
S26 20.145 E27 19.870	1.95E-01	3.67E-02			7.66E-02			1.07E-02	1.27E+00	6.76E-02	1.20E+00	7.91E-02	3.72E+00	4.86E-01	3.99E+00	1.33E-01
S26 20.145 E27 20.049	8.70E-02	2.42E-02			6.16E-02			9.96E-03	6.28E+00	4.70E-01	6.06E+00	4.72E-01	2.84E+00	4.70E-01	2.20E+00	1.04E-01
S26 20.145 E27 20.049	1.88E-01	4.56E-02			1.20E-01			1.72E-02	3.58E+00	1.36E-01	3.41E+00	1.37E-01	8.37E+00	7.21E-01	7.52E+00	1.67E-01
S26 20.145 E27 20.049	2.58E-01	4.46E-02			1.04E-01			1.64E-02	1.03E+01	7.95E-01	1.04E+01	7.99E-01	3.54E+00	5.10E-01	4.70E+00	1.37E-01
S26 20.187 E27 20.110	7.76E-02	2.04E-02			4.52E-02			6.17E-03	1.19E+00	4.19E-02	1.06E+00	4.77E-02	1.34E+00	3.98E-01	9.37E-01	7.20E-02
S26 20.187 E27 20.110	1.18E-01	7.22E-03			1.07E-02			1.55E-03	5.39E-01	1.08E-02	5.33E-01	1.39E-02	5.88E-01	3.42E-01	4.75E-01	6.04E-02
S26 20.192 E27 19.930	1.11E-01	2.43E-02			5.53E-02			8.14E-03	7.75E-01	2.98E-02	7.37E-01	4.06E-02	1.54E+00	4.09E-01	1.57E+00	8.63E-02
S26 20.192 E27 19.930	1.60E-01	2.64E-02			4.44E-02			6.27E-03	2.38E+00	1.87E-01	2.31E+00	1.90E-01	2.32E+00	3.89E-01	9.59E-01	8.49E-02
S26 20.193 E27 19.799	1.63E-01	2.79E-02			4.32E-02			6.19E-03	2.45E+00	1.14E-01	2.41E+00	1.19E-01	1.02E+00	3.75E-01	7.51E-01	6.75E-02
S26 20.193 E27 19.799	2.17E-01	3.27E-02			6.00E-02			8.72E-03	1.06E+00	4.15E-02	1.02E+00	5.54E-02	2.90E+00	4.31E-01	1.84E+00	1.01E-01
S26 20.194 E27 20.173	1.07E-01	3.02E-02			5.26E-02			8.39E-03	2.42E+00	1.76E-01	2.22E+00	1.78E-01	1.40E+00	4.03E-01	6.40E-01	6.32E-02
S26 20.194 E27 20.173	1.04E-01	9.03E-03			1.92E-02			3.07E-03	8.76E-01	4.09E-02	7.85E-01	4.08E-02	3.16E+00	4.94E-01	2.20E+00	9.87E-02
S26 20.194 E27 20.383	2.50E-01	3.45E-02			5.39E-02			6.56E-03	4.04E+00	2.64E-01	3.93E+00	2.68E-01	1.18E+00	3.85E-01	9.19E-01	7.17E-02
S26 20.194 E27 20.383	1.87E-01	4.00E-02			7.88E-02			1.47E-02	1.01E+00	3.27E-02	9.79E-01	5.36E-02	3.82E+00	5.29E-01	2.02E+00	9.45E-02
S26 20.195 E27 19.870	2.37E-01	3.45E-02			5.63E-02			9.07E-03	8.64E-01	2.80E-02	8.62E-01	4.46E-02	3.05E+00	4.42E-01	2.55E+00	1.12E-01
S26 20.195 E27 19.870	1.98E-01	7.90E-03			8.95E-03			1.42E-03	2.74E+00	2.29E-01	2.65E+00	2.30E-01	1.24E+00	2.99E-01	9.22E-01	8.21E-02
S26 20.195 E27 19.990	1.72E-01	2.89E-02			5.09E-02			7.59E-03	9.64E-01	2.92E-02	8.85E-01	4.33E-02	6.37E-01	3.44E-01	7.15E-01	6.74E-02
S26 20.195 E27 19.990	1.68E-01	3.05E-02			6.03E-02			7.84E-03	2.28E+00	1.91E-01	2.29E+00	1.94E-01	1.70E+00	4.19E-01	1.75E+00	9.00E-02
S26 20.242 E27 19.870	1.28E-01	2.25E-02			4.12E-02			6.27E-03	2.56E+00	1.85E-02	2.52E+00	3.22E-02	8.02E-01	3.59E-01	6.20E-01	6.42E-02
S26 20.242 E27 19.870	8.94E-02	2.40E-02			6.30E-02			9.47E-03	3.46E+00	2.55E-01	3.39E+00	2.58E-01	4.02E+00	5.00E-01	2.84E+00	1.18E-01

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	K-40		Cs-134			Cs-137			Calculated alpha and beta				Measured alpha and beta			
									alpha		beta		alpha		beta	
GPS Coordinates	Activity	Uncertainty	Activity	Uncertainty	MDA	Activity	Uncertainty	MDA	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 20.244 E27 20.049	1.02E-01	2.60E-02			3.66E-02			6.87E-03	1.19E+00	6.11E-02	1.12E+00	6.83E-02	1.29E+00	3.94E-01	8.29E-01	6.90E-02
S26 20.244 E27 20.049	8.93E-02	2.34E-02			5.06E-02			6.95E-03	6.24E-01	3.06E-02	6.01E-01	4.21E-02	8.56E-01	3.63E-01	6.46E-01	6.48E-02
S26 20.245 E27 20.110	1.08E-01	3.04E-02			5.86E-02			8.28E-03	6.82E-01	3.84E-02	6.05E-01	5.15E-02	6.37E-01	3.44E-01	7.01E-01	6.70E-02
S26 20.245 E27 20.110	1.53E-01	2.68E-02			6.01E-02			7.44E-03	1.96E+00	1.05E-01	2.02E+00	1.12E-01	2.20E+00	4.52E-01	1.35E+00	8.06E-02
S26 20.247 E27 19.930	8.85E-02	1.96E-02			4.42E-02			6.57E-03	1.21E+00	4.75E-02	1.07E+00	5.44E-02	9.56E-01	3.68E-01	1.03E+00	7.49E-02
S26 20.247 E27 19.930	9.08E-02	2.33E-02			5.11E-02			7.86E-03	1.26E+00	7.07E-02	1.27E+00	7.58E-02	1.39E+00	4.01E-01	9.39E-01	7.18E-02
S26 20.248 E27 19.991	1.82E-01	3.19E-02			6.17E-02			8.83E-03	2.67E+00	2.47E-02	2.65E+00	4.30E-02	4.15E-01	3.20E-01	8.95E-01	7.26E-02
S26 20.248 E27 19.991	1.10E-01	6.71E-03			1.26E-02	1.01E-03	3.90E-04	1.18E-02	1.57E+00	7.24E-02	1.45E+00	7.30E-02	1.28E+00	3.04E-01	1.15E+00	8.59E-02
S26 20.255 E27 19.798	2.39E-01	3.29E-02			5.26E-02			7.21E-03	3.29E+00	9.20E-02	3.18E+00	1.00E-01	2.44E+00	4.26E-01	1.02E+01	1.99E-01
S26 20.303 E27 20.390	9.98E-02	2.59E-02			4.55E-02			8.61E-03	3.53E+00	1.23E-01	3.42E+00	1.30E-01	1.65E+00	4.16E-01	1.57E+00	8.61E-02
S26 20.303 E27 20.390	2.38E-01	4.18E-02			7.84E-02			1.19E-02	1.90E+00	8.95E-02	1.98E+00	1.01E-01	3.10E+00	5.02E-01	2.47E+00	1.02E-01
S26 20.306 E27 19.870	1.62E-01	2.71E-02			4.34E-02			5.66E-03	9.07E-01	3.33E-02	8.38E-01	4.52E-02	4.74E-01	3.29E-01	7.18E-01	6.79E-02
S26 20.306 E27 19.870	1.20E-01	2.33E-02			4.33E-02			7.10E-03	1.51E+00	6.81E-02	1.45E+00	7.41E-02	1.93E+00	3.61E-01	1.28E+00	8.93E-02
S26 20.451 E27 19.645	1.28E-01	2.59E-02			4.55E-02			7.12E-03	2.08E+00	1.13E-01	2.00E+00	1.17E-01	2.90E+00	4.80E-01	1.63E+00	8.77E-02
S26 20.458 E27 19.645	6.75E-02	2.68E-02			5.46E-02			7.88E-03	1.21E+00	3.35E-02	1.07E+00	4.71E-02	1.39E+00	4.00E-01	1.21E+00	7.86E-02
S26 20.465 E27 19.645	1.01E-01	2.49E-02			3.84E-02			7.66E-03	1.43E+00	3.20E-02	1.34E+00	4.28E-02	1.61E+00	3.34E-01	1.26E+00	8.84E-02
S26 20.820 E27 19.114	1.00E-01	2.64E-02			5.70E-02			8.70E-03	1.60E+00	1.38E-01	1.50E+00	1.42E-01	1.39E+00	3.14E-01	1.22E+00	8.73E-02
S26 20.825 E27 19.114	1.90E-01	3.05E-02			5.84E-02			9.78E-03	2.74E+00	1.76E-01	2.75E+00	1.80E-01	5.10E+00	5.57E-01	3.04E+00	1.22E-01
S26 20.830 E27 19.114	9.44E-02	2.32E-02			5.43E-02			8.87E-03	1.72E+00	8.99E-02	1.82E+00	9.49E-02	1.54E+00	4.09E-01	1.62E+00	8.74E-02
S26 21.256 E27 18.366	2.48E-01	3.98E-02			8.97E-02			1.30E-02	3.41E+00	1.49E-01	3.47E+00	1.58E-01	2.94E+00	4.93E-01	2.21E+00	9.76E-02
S26 21.256 E27 18.383	2.19E-01	5.68E-02			1.79E-01			2.85E-02	1.74E+01	1.16E+00	1.71E+01	1.16E+00	2.05E+01	1.09E+00	1.37E+01	2.20E-01
S26 21.259 E27 18.402	1.15E-01	2.58E-02			5.57E-02			1.12E-02	3.04E+00	2.40E-01	2.73E+00	2.43E-01	3.53E+00	5.13E-01	2.66E+00	1.07E-01
S26 21.335 E27 18.117					5.40E-02			1.00E-02	1.08E+00	3.90E-02	8.24E-01	3.73E-02	8.02E-01	3.43E-01	5.99E-01	6.60E-02
S26 21.340 E27 18.117	2.90E-01	3.60E-02			6.72E-02			9.30E-03	4.25E+00	2.93E-01	4.37E+00	2.97E-01	3.50E+00	4.74E-01	4.24E+00	1.36E-01
S26 21.345 E27 18.117	2.22E-01	3.16E-02			5.92E-02			9.81E-03	2.23E+00	8.03E-02	2.15E+00	8.87E-02	1.28E+00	3.78E-01	1.05E+00	7.69E-02
S26 21.420 E27 17.712	1.20E-01	2.56E-02			5.04E-02			7.70E-03	1.74E+00	1.75E-01	1.70E+00	1.78E-01	2.09E+00	3.74E-01	1.40E+00	9.16E-02
S26 21.425 E27 17.712	2.15E-01	3.40E-02			5.66E-02			1.06E-02	2.72E+00	1.15E-01	2.68E+00	1.22E-01	3.11E+00	5.03E-01	2.08E+00	9.50E-02
S26 21.430 E27 17.712	2.19E-01	3.29E-02			5.37E-02			8.40E-03	1.26E+00	3.37E-02	1.21E+00	5.02E-02	1.33E+00	3.10E-01	1.60E+00	9.39E-02
S26 21.738 E27 16.822	1.06E-01	2.98E-02			6.33E-02			1.02E-02	2.16E+00	7.51E-02	2.01E+00	8.31E-02	2.20E+00	4.40E-01	1.18E+00	7.85E-02
S26 21.743 E27 16.822	1.58E-01	3.44E-02			5.77E-02			1.00E-02	1.62E+00	4.68E-02	1.38E+00	6.04E-02	1.23E+00	2.99E-01	8.85E-01	8.15E-02
S26 21.748 E27 16.822	1.97E-01	3.10E-02			5.25E-02			7.82E-03	1.05E+00	4.52E-02	1.03E+00	5.75E-02	6.31E-01	3.41E-01	1.01E+00	7.51E-02
S26 21.922 E27 15.989	2.73E-01	3.40E-02			5.13E-02			7.62E-03	1.74E+00	6.71E-02	1.65E+00	7.69E-02	1.23E+00	2.99E-01	1.27E+00	8.78E-02
S26 21.929 E27 15.989	2.28E-01	3.46E-02			6.97E-02			1.16E-02	5.13E+00	4.48E-01	5.13E+00	4.50E-01	5.02E+00	5.85E-01	4.39E+00	1.32E-01
S26 21.937 E27 15.989	3.07E-01	4.06E-02			5.99E-02			9.48E-03	1.52E+00	3.76E-02	1.51E+00	5.80E-02	2.11E+00	3.79E-01	2.00E+00	1.02E-01

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	K-40		Cs-134			Cs-137			Calculated alpha and beta				Measured alpha and beta			
									alpha		beta		alpha		beta	
GPS Coordinates	Activity	Uncertainty	Activity	Uncertainty	MDA	Activity	Uncertainty	MDA	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 22.160 E27 14.523	2.35E-01	1.11E-02	6.76E-03	3.56E-03	1.16E-02			2.22E-03	2.77E+00	9.60E-02	2.72E+00	9.88E-02	2.54E+00	4.15E-01	9.31E-01	6.72E-02
S26 22.160 E27 14.523	2.07E-01	2.93E-02			5.01E-02			7.35E-03	1.34E+00	5.17E-02	1.35E+00	5.99E-02	5.89E+00	5.95E-01	1.71E+00	8.24E-02
S26 22.170 E27 14.492	1.92E-01	2.84E-02			4.84E-02			6.52E-03	2.20E+01	1.59E+00	2.27E+01	1.60E+00	2.21E+00	3.93E-01	8.06E-01	6.40E-02
S26 22.170 E27 14.492					1.80E-01			2.61E-02	1.81E+01	1.30E+00	1.79E+01	1.30E+00	2.18E+01	1.10E+00	1.61E+01	2.37E-01
S26 22.170 E27 14.492	1.81E-01	4.12E-02			1.38E-01			1.93E-02	1.11E+00	5.88E-02	1.08E+00	6.64E-02	1.80E+01	1.00E+00	1.26E+01	2.10E-01
S26 22.182 E27 14.555	2.03E-01	2.98E-02			6.27E-02			9.42E-03	2.26E+00	1.00E-01	2.13E+00	1.06E-01	2.68E+00	4.23E-01	1.62E+00	8.38E-02
S26 22.182 E27 14.555	2.49E-01	4.11E-02			8.80E-02			1.25E-02	6.73E+00	4.80E-01	6.68E+00	4.83E-01	9.37E+00	7.57E-01	4.35E+00	1.32E-01
S26 22.189 E27 14.717	9.82E-02	6.65E-03			1.24E-02			1.89E-03	2.09E+00	1.30E-01	2.07E+00	1.30E-01	2.80E+00	4.75E-01	1.45E+00	8.40E-02
S26 22.190 E27 14.504	9.93E-02	2.63E-02			5.02E-02			7.76E-03	3.67E+00	9.43E-02	3.49E+00	1.00E-01	2.10E+00	4.27E-01	1.16E+00	8.40E-02
S26 22.190 E27 14.504	1.51E-01	2.92E-02			6.46E-02			1.07E-02	5.16E+00	2.89E-01	5.14E+00	2.93E-01	4.25E+00	5.46E-01	2.08E+00	1.00E-01
S26 22.190 E27 14.504	6.27E-02	2.59E-02			7.36E-02			1.23E-02	2.14E+00	6.35E-02	2.02E+00	7.13E-02	6.67E+00	6.55E-01	3.37E+00	1.20E-01
S26 22.194 E27 14.449	2.07E-01	3.69E-02			8.47E-02			1.23E-02	2.68E+00	1.45E-01	2.83E+00	1.52E-01	7.51E+00	6.62E-01	4.64E+00	1.31E-01
S26 22.194 E27 14.449	2.57E-01	4.62E-02			9.54E-02			1.47E-02	2.33E+00	7.20E-02	2.30E+00	8.22E-02	1.33E+00	3.23E-01	1.44E+00	8.15E-02
S26 22.194 E27 14.449	2.07E-01	3.82E-02			1.12E-02			8.12E-03	6.18E+00	4.75E-01	6.44E+00	4.78E-01	3.16E+00	4.51E-01	2.14E+00	9.40E-02
S26 22.197 E27 14.867	1.18E-01	2.99E-02			8.04E-02			1.31E-02	5.37E+00	3.00E-01	5.23E+00	3.04E-01	6.94E+00	6.70E-01	3.47E+00	1.17E-01
S26 22.198 E27 14.721	1.81E-01	2.67E-02			6.03E-02			9.09E-03	3.77E+00	3.07E-01	3.68E+00	3.09E-01	3.25E+00	4.56E-01	3.00E+00	1.19E-01
S26 22.203 E27 14.459	2.22E-01	1.22E-02			2.14E-02			3.31E-03	5.31E+00	1.65E-01	5.11E+00	1.67E-01	5.96E+00	5.95E-01	3.63E+00	1.17E-01
S26 22.203 E27 14.459	2.38E-01	5.31E-02			1.37E-01			2.20E-02	2.11E+01	1.38E+00	2.14E+01	1.38E+00	1.94E+01	1.05E+00	1.46E+01	2.30E-01
S26 22.205 E27 14.867	8.81E-02	2.49E-02			7.02E-02			1.00E-02	3.27E+00	1.56E-01	3.01E+00	1.60E-01	3.22E+00	4.98E-01	1.74E+00	8.95E-02
S26 22.206 E27 14.721	1.55E-01	3.08E-02			6.66E-02			9.43E-03	2.97E+00	1.41E-01	2.89E+00	1.46E-01	4.41E+00	5.22E-01	2.15E+00	9.30E-02
S26 22.213 E27 14.867	1.95E-01	3.32E-02			5.05E-02			7.65E-03	2.14E+00	1.56E-01	2.07E+00	1.61E-01	2.19E+00	3.82E-01	1.71E+00	9.71E-02
S26 22.214 E27 14.721	1.07E-01	2.47E-02			4.14E-02			4.67E-03	1.64E+00	4.85E-02	1.48E+00	5.72E-02	1.44E+00	3.20E-01	1.31E+00	8.89E-02
S26 22.240 E27 14.404	2.24E-01	4.16E-02			8.58E-02			1.13E-02	1.59E+00	9.62E-02	1.77E+00	1.07E-01	2.95E+00	4.39E-01	1.84E+00	8.82E-02
S26 22.240 E27 14.404	2.15E-01	4.22E-02			1.13E-02			7.21E-03	2.64E+00	1.26E-01	2.92E+00	1.36E-01	3.50E+00	4.72E-01	1.87E+00	8.83E-02
S26 22.240 E27 15.160	1.17E-01	3.98E-02			1.18E-01			1.88E-02	1.22E+01	7.54E-01	1.16E+01	7.56E-01	1.74E+01	1.01E+00	8.55E+00	1.74E-01
S26 22.244 E27 14.424	1.03E-01	2.68E-02			7.33E-02			1.04E-02	3.49E+00	1.40E-01	3.57E+00	1.45E-01	4.36E+00	5.20E-01	2.07E+00	9.15E-02
S26 22.244 E27 14.424	7.86E-02	2.32E-02			6.69E-02			9.99E-03	2.15E+00	2.29E-01	2.07E+00	2.30E-01	2.19E+00	3.89E-01	1.63E+00	8.46E-02
S26 22.245 E27 15.160	2.24E-01	5.01E-02			1.41E-01			2.32E-02	1.47E+01	1.01E+00	1.42E+01	1.01E+00	1.55E+01	9.52E-01	1.09E+01	1.98E-01
S26 22.250 E27 15.160	2.78E-01	6.62E-02			1.77E-01			2.59E-02	1.47E+01	9.98E-01	1.43E+01	1.00E+00	1.65E+01	9.81E-01	9.85E+00	1.88E-01
S26 22.267 E27 14.318	1.09E-01	2.15E-02			3.40E-02			5.95E-03	6.95E-01	3.16E-02	6.66E-01	4.01E-02	1.40E+00	3.32E-01	6.59E-01	6.11E-02
S26 22.267 E27 14.318	1.92E-01	3.26E-02			4.87E-02			7.28E-03	1.02E+00	6.03E-02	1.15E+00	6.57E-02	2.04E+00	3.80E-01	1.05E+00	7.10E-02
S26 22.267 E27 14.318	3.63E-01	4.03E-02			5.95E-02			8.64E-03	2.62E+00	1.58E-01	2.78E+00	1.64E-01	2.30E+00	3.96E-01	2.15E+00	9.53E-02
S26 22.267 E27 14.318	7.75E-02	2.52E-02			6.41E-02			1.01E-02	2.88E+00	2.10E-01	2.66E+00	2.13E-01	3.87E+00	4.93E-01	1.99E+00	9.04E-02
S26 22.267 E27 14.318	2.72E-01	4.05E-02			8.25E-02			1.34E-02	7.52E+00	5.65E-01	7.47E+00	5.68E-01	7.16E+00	6.72E-01	5.62E+00	1.50E-01

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									alpha		beta		alpha		beta	
GPS Coordinates	Activity	Uncertainty	Activity	Uncertainty	MDA	Activity	Uncertainty	MDA	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 22.282 E27 14.366	1.10E-01	2.84E-02			4.97E-02			8.18E-03	2.47E+00	1.50E-01	2.57E+00	1.54E-01	3.16E+00	4.52E-01	2.02E+00	9.16E-02
S26 22.282 E27 14.366	1.95E-01	4.08E-02			8.89E-02			1.21E-02	1.36E+00	1.00E-01	1.57E+00	1.11E-01	2.64E+00	4.20E-01	1.42E+00	7.96E-02
S26 22.293 E27 14.392	2.35E-01	3.94E-02			1.23E-02			8.94E-03	2.98E+00	2.82E-01	3.19E+00	2.86E-01	3.92E+00	4.95E-01	2.36E+00	9.76E-02
S26 22.293 E27 14.392	9.84E-02	2.88E-02			7.08E-02			1.02E-02	3.40E+00	3.20E-01	3.47E+00	3.23E-01	5.76E+00	5.87E-01	2.71E+00	1.02E-01
S26 22.308 E27 14.283	1.70E-01	3.10E-02			5.51E-02			7.98E-03	1.50E+00	1.14E-01	1.65E+00	1.19E-01	2.80E+00	4.31E-01	1.31E+00	7.66E-02
S26 22.308 E27 14.283	1.92E-01	3.18E-02			6.57E-02			7.59E-03	1.94E+00	8.17E-02	1.96E+00	8.92E-02	1.33E+00	3.24E-01	1.25E+00	7.72E-02
S26 22.308 E27 14.283	1.28E-01	2.20E-02			4.44E-02			7.38E-03	1.31E+00	7.33E-02	1.44E+00	7.84E-02	1.23E+00	3.66E-01	1.10E+00	8.42E-02
S26 22.320 E27 14.327	1.25E-01	2.68E-02			5.76E-02			7.84E-03	1.44E+00	6.23E-02	1.51E+00	6.96E-02	2.21E+00	3.93E-01	7.93E-01	6.35E-02
S26 22.320 E27 14.327	1.80E-01	3.60E-02			6.64E-02			9.36E-03	9.75E-01	4.47E-02	9.23E-01	6.05E-02	1.99E+00	3.77E-01	8.62E-01	6.60E-02
S26 22.320 E27 14.327	1.89E-01	3.48E-02			7.07E-02			1.05E-02	2.05E+00	9.96E-02	2.12E+00	1.08E-01	1.87E+00	3.66E-01	1.54E+00	8.31E-02
S26 22.327 E27 14.356	1.74E-01	3.63E-02			8.44E-02			1.25E-02	5.34E+00	3.65E-01	5.09E+00	3.68E-01	4.33E+00	5.53E-01	3.44E+00	1.18E-01
S26 22.330 E27 14.301	8.58E-02	2.80E-02			6.61E-02			1.11E-02	1.88E+00	8.84E-02	1.68E+00	9.58E-02	3.58E+00	4.75E-01	2.90E+00	1.07E-01
S26 22.330 E27 14.301	1.06E-01	2.84E-02			5.26E-02			7.21E-03	5.90E-01	2.10E-02	4.86E-01	3.77E-02	2.19E+00	3.89E-01	1.83E+00	8.88E-02
S26 22.330 E27 14.301	1.45E-01	2.74E-02			4.89E-02			8.80E-03	4.76E+00	3.23E-01	4.64E+00	3.25E-01	9.59E-01	2.92E-01	8.88E-01	6.87E-02
S26 22.330 E27 14.301	2.16E-01	3.55E-02			5.29E-02			8.35E-03	2.33E+00	1.58E-01	2.40E+00	1.63E-01	1.40E+00	3.32E-01	5.79E-01	5.84E-02
S26 22.330 E27 14.301	1.01E-01	2.72E-02			5.10E-02			7.62E-03	1.30E+00	5.33E-02	1.19E+00	6.25E-02	2.05E+00	3.81E-01	8.24E-01	6.47E-02
S26 22.330 E27 14.301	1.47E-01	2.66E-02			5.03E-02			5.38E-03	1.34E+00	5.23E-02	1.29E+00	6.13E-02	9.09E-01	2.88E-01	7.09E-01	6.37E-02
S26 22.330 E27 14.301	5.36E-02	1.89E-02			3.62E-02			6.77E-03	1.16E+00	4.94E-02	9.50E-01	5.58E-02	1.08E+00	3.05E-01	4.22E-01	5.39E-02
S26 22.330 E27 14.301	1.13E+00	6.93E-02			6.04E-02			1.03E-02	7.16E-01	2.80E-02	1.66E+00	7.60E-02	1.42E+00	3.28E-01	2.30E+00	9.86E-02
S26 22.330 E27 14.301	1.01E-01	2.18E-02			3.54E-02			6.57E-03	1.04E+00	4.38E-02	9.50E-01	5.15E-02	1.57E+00	3.46E-01	5.16E-01	5.57E-02
S26 22.330 E27 14.301	1.30E-01	2.80E-02			5.76E-02			1.01E-02	3.51E+00	3.26E-01	3.46E+00	3.28E-01	3.14E+00	4.86E-01	3.04E+00	1.17E-01
S26 22.330 E27 14.301	1.26E-01	2.68E-02			5.52E-02			8.74E-03	1.28E+00	4.57E-02	1.15E+00	5.51E-02	1.87E+00	4.11E-01	1.48E+00	9.14E-02
S26 22.330 E27 14.301	1.89E-01	2.98E-02			4.33E-02			6.25E-03	9.89E-01	4.53E-02	1.04E+00	5.68E-02	1.50E+00	3.24E-01	1.20E+00	8.71E-02
S26 22.338 E27 14.223	1.67E-01	2.83E-02			5.79E-02			8.91E-03	1.33E+01	7.58E-01	1.37E+01	7.60E-01	3.38E+00	4.64E-01	2.24E+00	9.57E-02
S26 22.338 E27 14.223	1.63E-01	3.86E-02			1.02E-01			1.55E-02	3.73E+00	2.07E-01	3.37E+00	2.10E-01	1.28E+01	8.69E-01	9.81E+00	1.91E-01
S26 22.346 E27 14.251	1.60E-01	2.94E-02			6.04E-02			9.25E-03	2.75E+00	1.05E-01	2.88E+00	1.11E-01	1.12E+00	3.07E-01	9.75E-01	7.07E-02
S26 22.346 E27 14.251	1.11E-01	2.56E-02			5.48E-02			7.94E-03	9.34E-01	4.98E-02	9.97E-01	5.82E-02	1.18E+00	3.11E-01	6.89E-01	6.20E-02
S26 22.346 E27 14.251	2.03E-01	3.00E-02			5.47E-02			9.04E-03	1.69E+00	7.70E-02	1.65E+00	8.47E-02	2.90E+00	4.74E-01	1.88E+00	9.78E-02
S26 22.358 E27 14.293	7.52E-02	2.08E-02			4.76E-02			6.69E-03	2.80E+00	1.60E-01	2.89E+00	1.64E-01	3.67E+00	4.83E-01	1.08E+00	6.94E-02
S26 22.358 E27 14.293	7.02E-02	2.69E-02			7.25E-02			1.11E-02	9.24E-01	5.10E-02	9.93E-01	5.95E-02	2.78E+00	4.27E-01	2.21E+00	9.68E-02
S26 22.365 E27 14.233	1.29E-01	2.47E-02			4.83E-02			6.75E-03	6.34E-01	3.74E-02	7.27E-01	4.71E-02	1.72E+00	3.57E-01	7.02E-01	6.16E-02
S26 22.365 E27 14.233	2.42E-01	3.60E-02			7.43E-02			1.01E-02	2.25E+00	1.74E-01	2.36E+00	1.78E-01	1.71E+00	3.54E-01	1.51E+00	8.21E-02
S26 22.365 E27 14.233	6.39E-02	1.79E-02			4.28E-02			7.36E-03	9.72E-01	7.16E-02	1.02E+00	7.55E-02	1.93E+00	3.61E-01	1.62E+00	9.52E-02
S26 22.367 E27 14.317	1.02E-01	2.58E-02			6.68E-02			9.74E-03	3.70E+00	2.81E-01	3.29E+00	2.83E-01	5.75E+00	5.87E-01	2.90E+00	1.06E-01

Empty spaces indicate a lower limit of determination value was obtained. See the end of the Table to find an indication of the lower limits

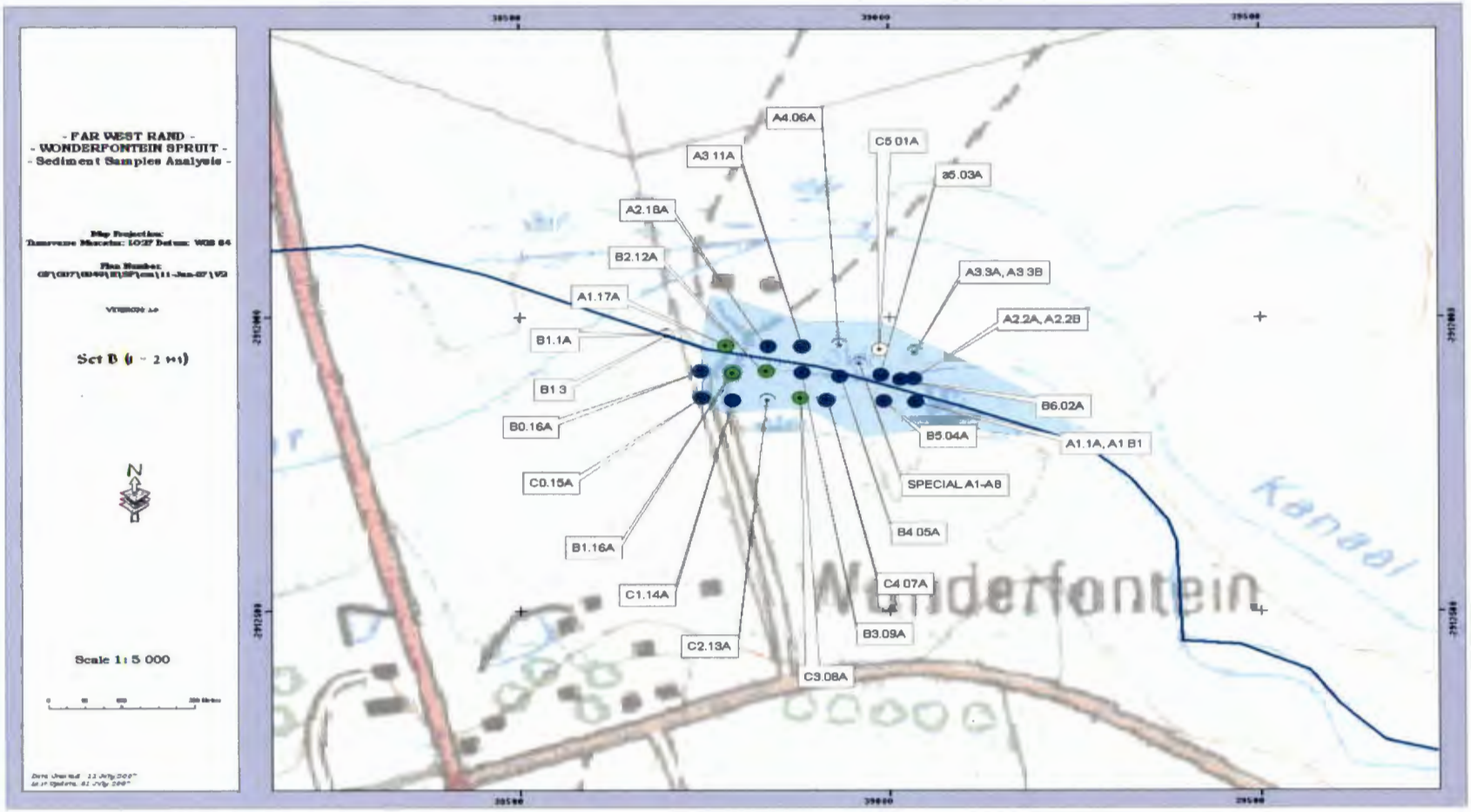
	K-40		Cs-134			Cs-137			Calculated alpha and beta				Measured alpha and beta			
									alpha		beta		alpha		beta	
GPS Coordinates	Activity	Uncertainty	Activity	Uncertainty	MDA	Activity	Uncertainty	MDA	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 22.378 E27 14.263	2.12E-01	3.54E-02			7.00E-02			8.99E-03	3.63E+00	3.19E-01	3.62E+00	3.22E-01	3.91E+00	5.28E-01	2.67E+00	1.11E-01
S26 22.387 E27 14.285	2.27E-01	3.76E-02			7.63E-02			1.16E-02	2.70E+00	1.50E-01	2.99E+00	1.57E-01	6.80E+00	6.34E-01	2.35E+00	9.48E-02
S26 22.613 E27 13.708	1.19E-01	2.58E-02			5.15E-02			9.36E-03	6.09E+00	3.19E-01	6.04E+00	3.21E-01	6.89E+00	6.43E-01	5.67E+00	1.57E-01
S26 22.646 E27 13.706	1.29E-01	2.87E-02			6.26E-02			1.08E-02	4.58E+00	3.35E-01	4.48E+00	3.38E-01	5.73E+00	5.89E-01	4.31E+00	1.40E-01
S26 22.655 E27 13.686	2.24E-01	3.43E-02			6.10E-02			8.58E-03	6.99E+00	5.15E-01	7.09E+00	5.19E-01	2.34E+00	3.95E-01	2.73E+00	1.14E-01
S26 22.655 E27 13.686	2.64E-01	4.94E-02			1.14E-01			1.78E-02	3.30E+00	1.86E-01	3.17E+00	1.94E-01	5.60E+00	6.11E-01	5.33E+00	1.44E-01
S26 22.660 E27 13.650	1.66E-01	3.75E-02			1.15E-01			1.68E-02	1.07E+01	7.37E-01	1.07E+01	7.39E-01	9.35E+00	7.58E-01	7.31E+00	1.65E-01
S26 22.699 E27 13.585	1.88E-01	3.21E-02			7.44E-02			1.14E-02	5.74E+00	4.41E-01	5.67E+00	4.44E-01	5.83E+00	5.95E-01	4.75E+00	1.45E-01
S26 22.699 E27 13.650	2.33E-01	4.84E-02			1.32E-01			1.83E-02	1.52E+01	6.26E-01	1.16E+01	6.15E-01	9.46E+00	7.62E-01	7.41E+00	1.66E-01
S26 22.722 E27 13.538					7.79E-02			1.07E-02	7.18E+00	4.29E-01	5.95E+00	4.23E-01	4.87E+00	5.79E-01	3.46E+00	1.18E-01
S26 22.725 E27 13.594	1.87E-01	4.73E-02			1.33E-01			2.15E-02	1.37E+01	1.03E+00	1.36E+01	1.03E+00	1.13E+01	8.22E-01	9.15E+00	1.83E-01
S26 22.744 E27 13.538	8.76E-02	2.81E-02			6.92E-02			1.08E-02	4.32E+00	1.67E-01	4.16E+00	1.71E-01	5.16E+00	5.94E-01	2.79E+00	1.07E-01
S26 22.778 E27 13.486	2.40E-01	4.38E-02			1.04E-01			1.54E-02	8.07E+00	5.92E-01	8.03E+00	5.95E-01	8.68E+00	7.16E-01	6.20E+00	1.65E-01
S26 22.778 E27 13.546	1.63E-01	3.23E-02			7.87E-02			1.12E-02	5.73E+00	3.54E-01	5.59E+00	3.56E-01	3.84E+00	5.28E-01	3.85E+00	1.25E-01
S26 22.805 E27 13.538	1.76E-01	3.54E-02			8.07E-02			1.21E-02	4.37E+00	3.19E-01	4.28E+00	3.23E-01	3.36E+00	5.03E-01	3.06E+00	1.13E-01
S26 22.814 E27 13.446	3.35E-01	5.51E-02			1.22E-01			1.91E-02	1.59E+01	8.32E-01	1.32E+01	8.21E-01	9.35E+00	7.58E-01	7.42E+00	1.66E-01
S26 22.814 E27 13.490	3.06E-01	4.06E-02			8.25E-02			1.28E-02	5.84E+00	4.97E-01	5.91E+00	5.00E-01	5.61E+00	6.11E-01	4.56E+00	1.34E-01
S26 22.831 E27 13.489	1.22E-01	2.51E-02			4.78E-02			6.12E-03	4.96E+00	3.71E-01	4.89E+00	3.72E-01	5.25E+00	5.66E-01	3.98E+00	1.35E-01
S26 22.831 E27 13.540	1.99E-01	8.23E-03			1.32E-02			1.96E-03	1.03E+01	6.16E-01	1.03E+01	6.17E-01	1.99E+00	3.72E-01	3.45E+00	1.24E-01
S26 22.831 E27 13.540	2.05E-01	3.65E-02			8.29E-02			1.36E-02	3.37E+00	1.87E-01	3.38E+00	1.91E-01	8.73E+00	7.23E-01	8.89E+00	1.91E-01
S26 22.853 E27 13.429	3.18E-01	4.99E-02			1.11E-01			1.49E-02	8.16E+00	4.10E-01	7.39E+00	4.07E-01	8.06E+00	7.13E-01	4.39E+00	1.30E-01
S26 22.859 E27 13.490	1.57E-01	3.70E-02			9.87E-02			1.52E-02	6.97E+00	5.74E-01	6.81E+00	5.77E-01	5.63E+00	6.10E-01	6.05E+00	1.52E-01
S26 22.859 E27 13.523	1.64E-01	4.58E-02			1.24E-01			2.01E-02	1.39E+01	6.12E-01	1.17E+01	6.02E-01	8.12E+00	7.13E-01	6.53E+00	1.57E-01
S26 22.871 E27 13.430	1.55E-01	2.66E-02			4.29E-02			6.92E-03	5.37E+00	4.43E-01	5.32E+00	4.45E-01	1.44E+00	3.20E-01	1.31E+00	8.90E-02
S26 22.871 E27 13.430	1.03E-01	2.30E-02			5.84E-02			9.19E-03	2.09E+00	6.50E-02	1.98E+00	7.06E-02	6.91E+00	6.43E-01	4.96E+00	1.49E-01
S26 22.877 E27 13.429	2.22E-01	4.89E-02			1.13E-01			1.83E-02	1.31E+01	7.69E-01	1.16E+01	7.68E-01	1.22E+01	8.55E-01	7.77E+00	1.68E-01
S26 22.882 E27 13.490	2.02E-01	4.03E-02			8.18E-02			1.30E-02	4.42E+00	2.64E-01	4.10E+00	2.68E-01	1.76E+00	4.10E-01	1.68E+00	9.05E-02
S26 22.902 E27 13.156	1.03E-01	3.04E-02			5.77E-02			8.84E-03	2.44E+00	1.07E-01	2.38E+00	1.14E-01	3.06E+00	4.90E-01	1.64E+00	8.76E-02
S26 22.934 E27 13.156	1.69E-01	3.33E-02			6.84E-02			1.12E-02	2.79E+00	1.38E-01	2.66E+00	1.44E-01	2.11E+00	4.34E-01	1.69E+00	8.99E-02
S26 22.938 E27 13.127	1.10E-01	3.47E-02			8.84E-02			1.41E-02	4.15E+00	1.83E-01	4.18E+00	1.89E-01	6.83E+00	6.37E-01	3.78E+00	1.34E-01
S26 22.938 E27 13.127	1.43E-01	2.74E-02			7.32E-02			1.10E-02	4.21E+00	3.33E-01	4.08E+00	3.35E-01	4.83E+00	5.78E-01	2.83E+00	1.08E-01
S26 22.938 E27 13.127	1.77E-01	3.47E-02			7.89E-02			1.17E-02	6.15E+00	3.41E-01	6.22E+00	3.45E-01	3.79E+00	5.26E-01	3.06E+00	1.13E-01
S26 22.944 E27 13.105	1.18E-01	3.03E-02			7.55E-02			1.16E-02	2.41E+00	8.40E-02	2.21E+00	9.27E-02	2.25E+00	4.43E-01	1.33E+00	8.19E-02
S26 22.964 E27 13.106	2.57E-01	4.53E-02			9.01E-02			1.57E-02	7.77E+00	3.73E-01	7.67E+00	3.78E-01	8.54E+00	7.09E-01	4.98E+00	1.50E-01

Empty spaces indicate a lower limit of determination value was obtained. See the end of the Table to find an indication of the lower limits

	K-40		Cs-134			Cs-137			Calculated alpha and beta				Measured alpha and beta			
									alpha		beta		alpha		beta	
GPS Coordinates	Activity	Uncertainty	Activity	Uncertainty	MDA	Activity	Uncertainty	MDA	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty	Activity	Uncertainty
S26 22.982 E27 12.976	1.41E-01	3.55E-02			9.56E-02			1.37E-02	7.82E+00	4.69E-01	7.69E+00	4.72E-01	6.47E+00	6.48E-01	5.18E+00	1.41E-01
S26 22.982 E27 13.041	2.31E-01	3.42E-02			7.54E-02			1.19E-02	6.60E+00	5.11E-01	6.61E+00	5.14E-01	8.46E+00	7.08E-01	6.07E+00	1.62E-01
S26 22.985 E27 12.924	1.07E-01	2.87E-02			5.82E-02			5.61E-03	3.68E+00	3.07E-01	3.19E+00	3.10E-01	3.64E+00	5.19E-01	2.42E+00	1.02E-01
S26 22.994 E27 13.106	2.26E-01	3.68E-02			7.01E-02			1.17E-02	2.74E+00	7.82E-02	2.56E+00	9.00E-02	1.76E+00	4.09E-01	1.61E+00	8.87E-02
S26 23.014 E27 12.976	1.25E-01	6.51E-03			1.10E-02			1.70E-03	2.73E+00	8.12E-02	2.69E+00	8.17E-02	3.71E+00	4.81E-01	2.18E+00	1.07E-01
S26 23.016 E27 12.924	2.59E-01	4.63E-02			9.39E-02			1.43E-02	5.37E+00	3.64E-01	5.42E+00	3.69E-01	4.04E+00	5.37E-01	4.00E+00	1.27E-01
S26 23.019 E27 13.040	1.17E-01	9.90E-03			1.69E-02			2.61E-03	1.65E+00	9.21E-02	1.59E+00	9.28E-02	1.66E+00	4.04E-01	1.22E+00	8.05E-02
S26 23.044 E27 12.856	1.11E-01	3.60E-02			9.63E-02			1.53E-02	8.03E+00	4.16E-01	8.07E+00	4.20E-01	6.40E+00	6.44E-01	5.65E+00	1.47E-01
S26 23.075 E27 12.856	2.19E-01	3.71E-02			6.88E-02			1.10E-02	4.56E+00	2.66E-01	4.48E+00	2.70E-01	4.33E+00	5.19E-01	3.66E+00	1.30E-01
S26 23.098 E27 12.785	1.34E-01	3.10E-02			5.36E-02			8.95E-03	2.17E+00	9.21E-02	2.06E+00	9.89E-02	2.63E+00	4.65E-01	1.39E+00	8.28E-02
S26 23.098 E27 12.856	1.35E-01	2.61E-02			4.45E-02			6.07E-03	6.40E+00	5.59E-01	6.29E+00	5.61E-01	1.82E+00	4.15E-01	1.13E+00	7.79E-02
S26 23.098 E27 12.856	1.56E-01	3.86E-02			9.22E-02			1.33E-02	1.58E+00	8.15E-02	1.60E+00	9.20E-02	4.03E+00	5.36E-01	4.60E+00	1.35E-01
S26 23.119 E27 12.785	2.53E-01	1.43E-02			2.37E-02			3.80E-03	4.46E+00	1.57E-01	4.53E+00	1.59E-01	4.71E+00	5.71E-01	3.56E+00	1.20E-01
Average	1.74E-01				6.56E-02			1.02E-02	3.90E+00		3.78E+00		4.00E+00		2.77E+00	
Standard deviation	9.87E-02				3.01E-02			4.60E-03	3.74E+00		3.62E+00		3.66E+00		2.60E+00	
Maximum	1.13E+00				1.80E-01			2.85E-02	2.20E+01		2.27E+01		2.18E+01		1.61E+01	
Minimum	4.04E-02				8.95E-03			1.17E-03	3.90E-01		4.49E-01		4.15E-01		2.16E-01	
Median	1.63E-01				5.85E-02			9.28E-03	2.59E+00		2.57E+00		2.80E+00		1.85E+00	

Empty spaces indicate a lower limit of determination value was obtained. See the end of the Table to find an indication of the lower limits

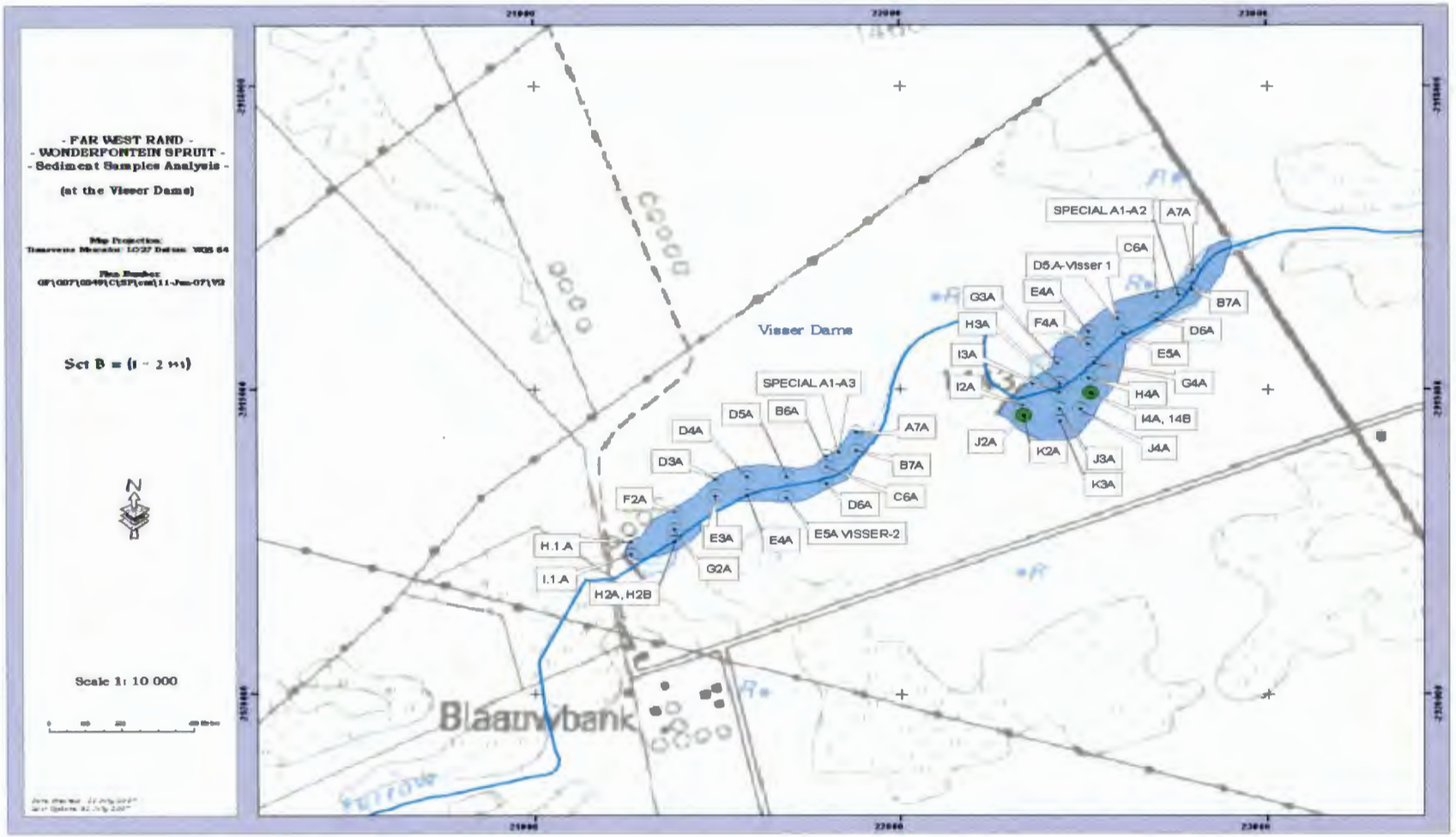
Appendix 3 Wonderfonteinspruit catchment area maps showing some sampling points



Sampling points at the Harry's dam

Sampling points in the Welverdiend area

Sampling points at the Coetzee dam



Sampling points in the Visser Dam