REPORT
ON THE
RADIOACTIVITY MONITORING
PROGRAMME
IN THE MOOI RIVER
(WONDERFONTEINSPRUIT)
CATCHMENT

INSTITUTE FOR WATER QUALITY STUDIES
DEPARTMENT OF WATER AFFAIRS AND FORESTRY

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A note of gratitude must also be extended to the sampling teams, and the staff of the respective analytical laboratories who undertook sample analysis.

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NOTE: While the compilation of this report was the responsibility of the Institute for Water Quality Studies, every attempt was made to incorporate the views of members of the Co-ordinating Committee, and this was to a large extent achieved. Mr A McLaren did not accept the report.

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REPORT ON THE RADIOACTIVITY MONITORING PROGRAMME IN THE MOOI RIVER (WONDERFONTEINSPRUIT) CATCHMENT.

EXECUTIVE SUMMARY

A radioactivity monitoring study was conducted by the Institute for Water Quality Studies (IWQS) of the Department of Water Affairs and Forestry (DWAF) in collaboration with a wide group of interested parties, in the Mooi River Catchment during 1997. The study served to establish the drinking water health risk, as well as the radiological status of the water resources, in the catchment from the viewpoint of drinking water. The intensive monitoring, both in time as well as in number of radionuclides measured served to clear up many areas of doubt, and has established with reasonable certainty the representative radiological status of the water resources in the catchment. The study covered surface streams and groundwater sources in the catchment. The evaluation of health risk was based on the levels of radioactivity in raw water samples that had been filtered prior to analysis, and on the use of such water for drinking purposes on a continuous basis. The relative contributions to the health risk from ingestion of the suspended solids in the water and from radiation exposure scenarios other than drinking water use were, with the possible exception of fish consumption, shown to be insignificant. The study did not consider radioactivity in sediments.

The radiological variables measured were all from the natural radioactive decay chains of uranium-238, uranium-235, and thorium-232. In addition to radiological variables, a full set of chemical variables was also monitored.

The radiation doses calculated in the study were based on the conservative assumption that the water at every sampling point was used continuously as the sole source of drinking water.

In view of the controversy surrounding the radiological status of water sources in the catchment, extensive efforts were made to validate the accuracy of the radiological measurements, as well as to cross check the validity of the total yearly doses calculated for each monitoring point. The total yearly dose was independently calculated by two different methods, which gave very similar radiation doses.

The set of dose criteria, used to evaluate the dose values found for drinking water, ranged from the ideal level of the World Health Organisation of 0,1 mSv/year, through the 0,25 mSv/year single facility dose limit used by the Council for Nuclear Safety, to the 1,0 mSv/year dose limit of the International Atomic Energy Agency for public exposure from anthropogenic sources. These dose criteria have been incorporated into proposed interim radioactivity water quality guidelines, with associated actions and interpretation.

The natural background radiation dose in drinking water in the catchment was estimated at 0,020 mSv/year. The great majority of sampling sites in the catchment showed a total drinking water radiation dose below 0,1 mSv/year, implying that no radiological problem exists from the viewpoint of drinking water. The general conclusion was that of the 41 sites monitored, 39 showed a water quality which is either ideal or acceptable for continuous lifetime use in terms of the proposed interim water quality guidelines for radioactivity in drinking water. Five sites had a dose between 0,1 and 0,25 mSv/year, showing a slightly larger increase above local natural background, but still fully acceptable for lifetime use with no significant detrimental effects to the user. Only two sites had significant elevation of the radiation dose which showed the need for planning to reduce the exposure over the course of time. Both these sites involved the discharge of mine water that had been pumped to the surface.

A highly relevant and comforting finding of the study was that the total radiation dose for both Potchefstroom untreated raw drinking water supply points was very low, and in fact not significantly different from the natural background dose value estimated for the study.

A valuable finding of the study was the good linear correlation between total radiation dose from all radionuclides and the uranium concentration. This will, in the future, make it possible to use the uranium concentration for screening and routine monitoring purposes within the catchment.

As regards the two classical screening parameters for radiation, viz., alpha and beta activity, the former showed a reasonably good correlation with total radiation dose, when compared on an annual average basis. The gross beta activity measurements were considered to be unreliable because of measurement difficulties at the low levels encountered. As regards chemical variables, while it was found that elevated radiation dose is usually associated with elevated sulphate concentrations, the converse was not true, consequently sulphate concentration cannot be used as an indicator of radioactivity in the water.

The water analysis technique involves filtering of the raw water samples prior to radiometric analysis, and the primary intention of the study was to measure only the radioactivity in the water passing through the filter. In the final month of the study, however, the radioactivity in the suspended solids trapped by the filter was also measured, as a preliminary indication of whether the suspended solids were of any significance as regard the possible radiation dose from ingestion of untreated water.

While an important aim of the study was to measure the concentrations of a large range of radionuclides in the natural uranium and thorium decay chains, it was not the intention to look at radon gas dissolved in the water. Dissolved radon, even at relatively high concentrations, does not contribute significantly to the drinking water health risk, and is generally considered to be of possible concern only where significantly elevated radon concentrations are associated with conditions that promote the dissolution and release of the gas into poorly ventilated enclosures. Such scenarios, which might include indoor spa baths and underground water treatment plants, are not known to exist in the Mooi River catchment.

1. INTRODUCTION

1.1 Background

Preliminary screening surveys of radioactivity in water sources was carried out by the Institute for Water Quality Studies in 1995 and 1996 [1,2]. The levels of the radioactive elements uranium and radium, found in streams in the vicinity of gold mining activities, were found to be elevated such that, in some cases, these streams might be regarded as unsuitable for continuous lifetime use as drinking water. Many radionuclides had not been measured, and there was no information on the variability of the radionuclide concentrations in the water sources. Due to the lack of detailed and definitive data on radionuclide concentrations, it was not possible to determine the safety or otherwise of the water sources when used for drinking water purposes without a more thorough and intensive monitoring programme. In order to obtain certain knowledge on the radiological status of the water sources to establish human health risk, it was essential that a more detailed investigation be conducted. This report summarizes the findings of an intensive radiological monitoring programme that was conducted in the Mooi River catchment during 1997.

1.2 Aims of the Study and Strategy Adopted

The aims of the radioactivity monitoring programme were:

(i) To measure and report on the most important radioactive components in surface streams and in groundwater at selected sampling locations, at regular intervals over a hydrological year.

(ii) To establish the radiation dose from untreated water for the purposes of use as drinking water, the emphasis being placed on the dissolved component of the radionuclides present in the water samples, and not on the suspended component.

(iii) To estimate, from such measurements, the incremental radiation doses above estimated background that could be received by users of the water.

(iv) To establish, on the basis of international practice, guidelines for interpreting the significance of these incremental radiation doses with a view to identifying the need for remedial action at any particular location. The recommendations would be brought to the attention of the relevant authorities within DWAF.

(v) To identify where further investigative work, beyond the scope of this study, was needed.

(vi) To identify strategies for efficient monitoring.

For clarity it is important to note what the study aims did not address. The study focussed on the radioactivity status of raw water, filtered before analysis. Some preliminary work was done on the suspended solids. All the possible uptake routes were investigated in detail, of which only the drinking water route and possibly the fish consumption route were found to be significant. Sediments, dissolved radon gas and airborne gas and dust were outside the scope of the study.

The strategy adopted to achieve the aims comprised the following:

(a) To focus on one catchment at a time, in order of priority - the Mooi River catchment (also known as and also containing the Wonderfonteinspruit catchment) was selected as the first catchment to be studied, and forms the basis of this report.

(b) To undertake the monitoring programme in a coordinated, transparent manner with the participation of relevant governmental and non-governmental stakeholders.

1.3 Management and Co-ordination of the Programme

The IWQS was responsible for the management and coordination of the radioactivity monitoring programme in the Mooi River catchment. The establishment of a Coordinating Committee and Technical Committee, involving representation from a wide spectrum of organizations interested or involved in monitoring of radioactivity, assured transparency and the involvement of a range of scientific opinion and decision making on the issue. The Coordinating Committee consisted of numerous individuals and role players including Rand Water, Goldfields Water, the Western Transvaal Water Company, the Lower Wonderfonteinspruit Catchment Forum, Anglogold Limited, Gold Fields of South Africa and other representative mining companies such as Randfontein Estates, the School of Chemical Engineering of the University of Potchefstroom, the Directorate: Water Quality Management and the Gauteng Regional Office of DWAF, the Council for Nuclear Safety (CNS), the Atomic Energy Corporation (AEC), the Chamber of Mines, the Council for Geoscience and the Department of Minerals and Energy.

The Technical Committee included representation from the AEC, the Chamber of Mines, the Gauteng Regional Office, the Council for Geoscience, the Council for Nuclear Safety, and the IWQS.

2. MONITORING PROGRAMME

2.1 Selection of Catchment

The Mooi River Catchment (Figures 1 and 2), was selected as the first priority catchment for intensive radioactivity monitoring for reasons including the following:

(i) Major gold mining activity is carried out in the region, with the potential for pollution of surface and ground water. The region has several large active gold mines which discharge fissure and process water into the aquatic environment.

(ii) The upper section of the catchment has numerous diffuse sources from old and abandoned mine workings and mine residue deposits.

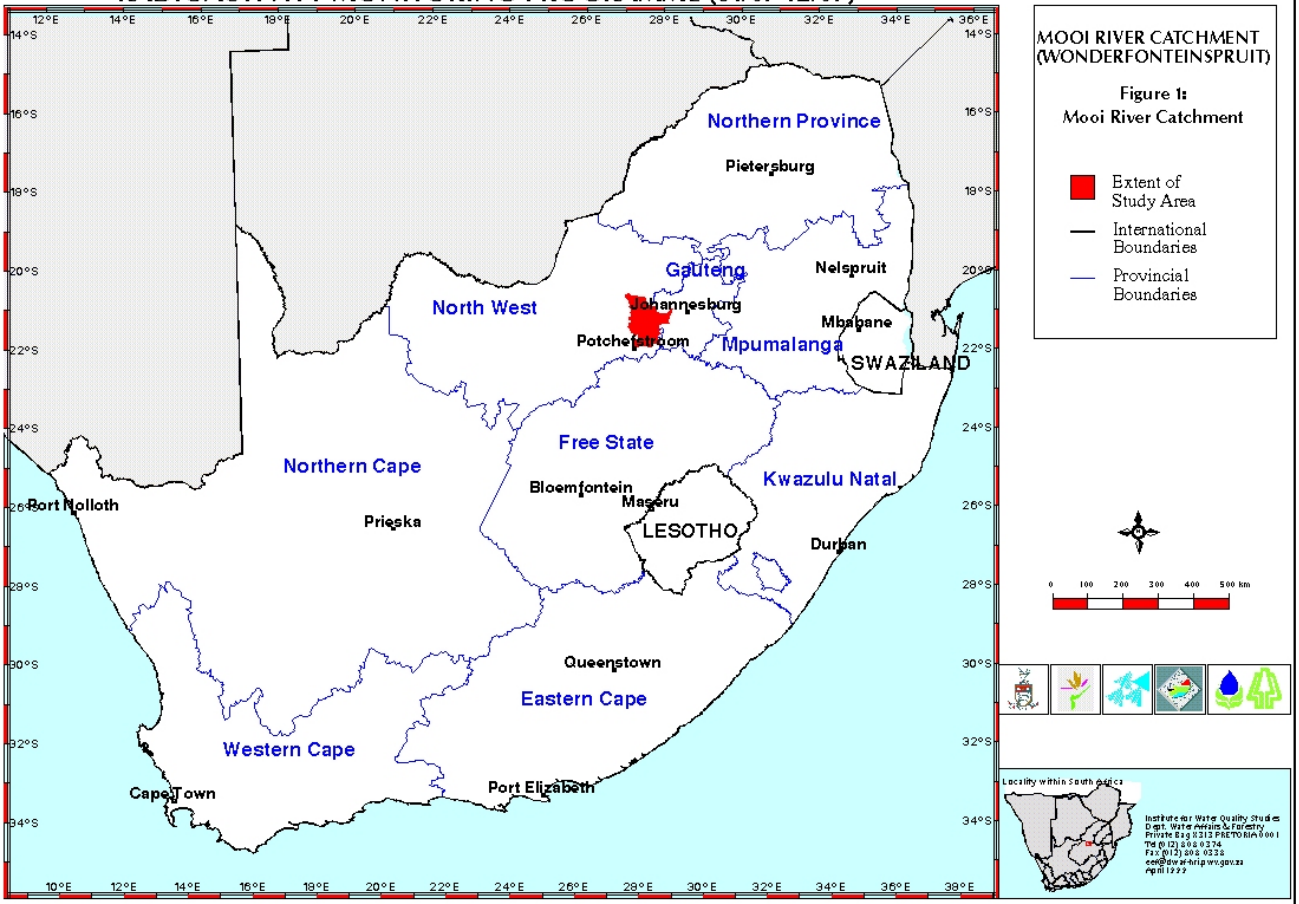
(iii) There are many informal settlements within the region, giving rise to possible consumption of untreated surface and ground water.

(iv) Formal townships, closely related to the mining activities, occur in the catchment. Carletonville municipality abstracts a small portion for water use from boreholes and Potchefstroom municipality abstracts water from the Boskop dam for domestic water use. During the course of the study, questions were raised regarding elevated levels of radioactivity in streams, within the catchment, that could have a negative impact on the quality of the untreated raw water supplied to Potchefstroom, located at the lower end of the catchment.

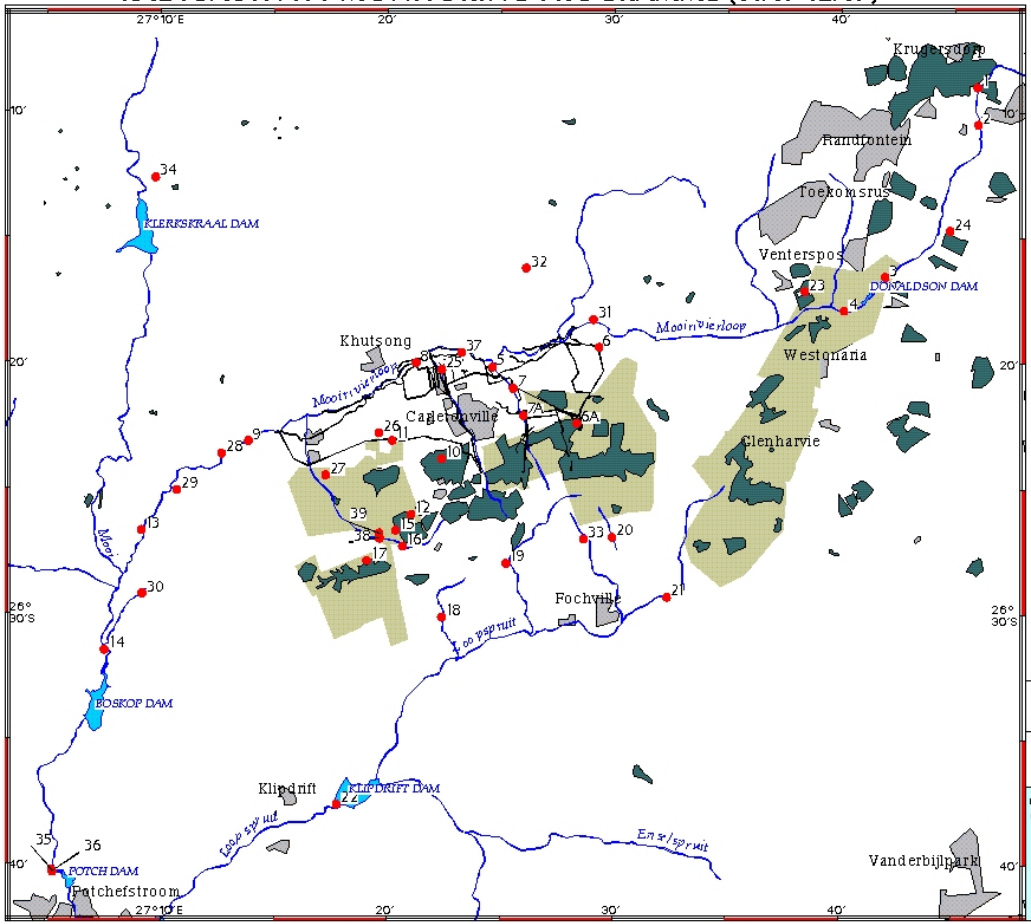
2.2 Characterisation of the Mooi River Catchment and Water Use

The Mooi River catchment consists of the Mooi River, Wonderfontein Spruit (Mooi River Loop) and Loop Spruit. The various dams situtated in the catchment include the Donaldson, Klipdrift, Boskop and Potchefstroom (Lakeside) Dams. The catchment is situated on the Far West Rand with the upper section in the Gauteng Province and the lower part of the catchment in the North West Province. The Mooi River and its tributaries receive contamination from a wide variety of point and diffuse sources. The headwaters of the Wonderfontein Spruit originate around the mine residue deposits of several old and abandoned mines. These mine tailings dams, sand dumps and rock dumps are potentially significant contributors to diffuse contamination. Furthermore, numerous active gold mines are discharging fissure and process water into the water environment.

RADIOACTIVITY MONITORING PROGRAMME (01/97-12/97)



RADIOACTIVITY MONITORING PROGRAMME (01/97-12/97)



MOOI RIVER CATCHMENT
(WONDERFONTEINSPRUIT)

Figure 2:
Sampling sites

- Towns
- Mines (CSIR)
- Mines (Goldfields)
- Rivers and Dams
- Canals

0 4 8 12 16 20 km

Locality within South Africa

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Most of the area is underlain by dolomite of which three of the dolomite compartments are dewatered by the gold mines. The water in the Wonderfontein Spruit is diverted into a one-metre diameter pipeline, which transports the water over two of the dewatered compartments. The Mooi River and its tributaries run through the magisterial districts of Potchefstroom, Westonaria, Oberholzer, Fochville and Carletonville. A number of growing communities are located in the catchment, including Kagiso, Mohlakeng, Toekomsrus, Rietvallei and Bekkersdal. These developments, as well as informal developments, contribute to the diffuse sources of pollution.

Rand Water supplies nearly all the water required for domestic use in the area, excluding Potchefstroom and the lower Mooi River area which is supplied by Potchefstroom municipality from the Boskop Dam. Carletonville Municipality sometimes extracts water for Welverdiend from a borehole in the Turffontein compartment.

Industrial use of water from the Mooi River is concentrated in and around Potchefstroom. Some water is abstracted by farmers along the lower reaches of the river for livestock watering and domestic supplies. The Mooi River is further used for angling and general recreational purposes.

Data on water usage by the various informal communities in the catchment were gathered primarily to establish usage for drinking water purposes (Appendix 1). This was important for determining the degree of conservatism inherent in assuming sole continuous use of the water for drinking purposes.

2.3 Selection of Monitoring Sites

During the initial stages of the monitoring programme 39 sampling locations (28 surface water sites, and 11 groundwater sites) were selected on the recommendation of the Gauteng Regional Office (Figure 2). Sampling was started in January 1997. In addition to the sites selected initially, the two untreated, raw water abstraction points at the Potchefstroom purification works were added, some time after initiation of the monitoring programme.

Table 1 summarises the sampling site information and identifies the location of the sites.

TABLE 1: Site, station numbers and monitoring point names, together with positional data.

Station number	Site No	Monitoring Point Name	Waterbody Name	Latitude	Longitude
C2H152Q01	1	Luipaardsvlei (At rail bridge from Turk Shaft to 1st West Gm	Wonderfontein Spruit [C2]	26°08'23"	27°46'00"
C2H153Q01	2	Rietvlei (Randfontein Azaadville bridge)	Wonderfontein Spruit [C2]	26°09'52"	27°46'02"
C2H154Q01	3	Luipaardsvlei (Doornkop Randfontein (R559) road bridge)	Wonderfontein Spruit [C2]	26°15'57"	27°41'58"
C2H025Q01	4	No 7 At Gemsbokfontein	Wonderfontein Spruit [C2]	26°17'18"	27°40'09"
C2H080Q01	5	Wonderfontein-End of 1m Pipe from Venterspost Gold Mine	Venterspost Gold Mine-Transfer [C2]	26°19'35"	27°24'38"
C2H030Q01	6	Oog Van Wonderfontein-Canal from Wonderfontein Eye	Wonderfontein Eye [C2]	26°18'47"	27°29'20"
C2H155Q01	6A	West Driefontein (down stream North Shaft Purification Works)	West Driefontein Gm-Fissure Water [C2]	26°21'49"	27°28'22"
C2H063Q01	7	Canal at Rooipoort	West Driefontein Gm-Transfer [C2]	26°20'26"	27°25'33"
C2H156Q01	7A	Carltonville West Driefontein Gm-C.Ville Cemetary Road Bridge	West Driefontein Gm-Process Water [C2]	26°21'31"	27°26'00"
C2H157Q01	8	Wonderfontein-Low water bridge to Abe Bailey Nature Reserve	Mooirivierloop [C2]	26°19'25"	27°21'15"
C2H069Q01	9	Blaauwbank	Mooirivierloop [C2]	26°22'32"	27°13'51"
C2H158Q01	10	Blyvooruitzicht Gold Mine-discharge To Doornfontein canal east of Pw	Blyvooruitzicht Gm-Fissure Water [C2]	26°23'15"	27°22'24"
C2H159Q01	11	Doornfontein Gm-Gold Plant discharge in canal upstream Doornfontein excess	Doornfontein Gm-Fissure Water [C2]	26°22'31"	27°20'12"
C2H160Q01	12	Doornfontein Gold Mine-Number 3 Shaft discharge	Doornfontein Gm-Fissure Water [C2]	26°25'29"	27°21'02"
C2H161Q01	13	Turffontein-gravel road bridge to Muiskraal	Mooirivierloop [C2]	26°26'05"	27°09'07"
C2H162Q01	14	Gerhard Minnebron-Rysmierbult road bridge upstream of Boskop Dam	Mooirivierloop [C2]	26°30'52"	27°07'29"
C2H163Q01	15	Western Deep Levels-farm bridge downstream of No 7 Shaft Slimes Dam	Varkenslaagte Spruit [C2]	26°26'06"	27°20'22"
C2H164Q01	16	Buffelsdoorn-Elandsrand Gold Mine	Elandsrand Gm-W Nursery Dam Overflow[C2]	26°26'44"	27°20'40"
C2H165Q01	17	Deelkraal Gold Mine recreational dam overflow	Deelkraal Dam-Outlet [C2]	26°27'18"	27°19'05"
C2H166Q01	18	Buffelsdoorn-Johannesburg/Potchefstroom road bridge	Buffelsdoorn Spruit [C2]	26°29'33"	27°22'24"
C2H167Q01	19	Elandsfontein-Johannesburg/Potchefstroom road bridge	Elandsfontein Spruit [C2]	26°27'24"	27°25'15"
C2H168Q01	20	Kraalkop-Old Johannesburg/Potchefstroom road bridge	Kraalkop Spruit [C2]	26°26'21"	27°29'56"
C2H169Q01	21	Weltevreden-Losberg/Bank road bridge	Loop Spruit [C2]	26°28'44"	27°32'22"
C2H170Q01	22	Klipdrift Dam-Outflow into concrete irrigation canal	Loop Spruit [C2]	26°37'01"	27°17'46"
C2H171Q01	23	Gempost-Venterspost Gold Mine Pipe from No 5 Shaft	Venterspos Gold Mine-Fissure Water [C2]	26°24'29"	27°10'42"
ZLUIPAAR1	24	Plot 40 Luipaardsvlei-35m south east of farm house	Borehole [C]	26°14'06"	27°44'49"
ZCARLTON1	25	Plot No 9 Carltonville	Borehole [C]	26°19'41"	27°22'24"
ZWELVER1	26	Plot at Welverdiend	Borehol [C]	26°22'13"	27°19'38"
ZWELVER2	27	Welverdiend municipal water supply 2km south of Welverdiend	Borehole [C]	26°23'54"	27°17'16"
ZBLAAUB1	28	Blauubank 100m east of house	Borehole]	26°23'03"	27°12'40"
C2H013Q01	29	Turffontein	Upper Turffontein Eye [C2]	26°24'29"	27°10'42"
C2H011Q01	30	Gerhardminnebron	Gerhardminnebron Eye [C2]	26°28'37"	27°09'09"
ZWONDER1	31	Oog Van Wonderfontein 110 between piggery buildings	Borehole [C]	26°17'41"	27°29'05"
ZDEPAN1	32	Plot 84 De Pan	Borehole [C]	26°15'38"	27°26'07"
ZKRAALK1	33	Plot Kraalkop	Borehole [C]	26°26'26"	27°28'40"
C2H172Q01	34	Bovenste Oog Van Mooirivier	Bovenste Oog [C2]	26°12'02"	27°09'45"
C2H173Q01	35	Mooi River: Potchefstroom Purification Works-Western abstraction point from canal	Boskop Dam-Outlet [C2]	26°39'37"	27°05'09"
C2H174Q01	36	Mooi River: Potchefstroom Purification Works-eastern abstraction point	Potchefstroom Dam-Outlet [C2]	26°39'42"	27°05'11"
C2H175Q01	37	Harry's Dam (Uitspanning at Wonderfontein)	Wonderfontein Spruit [C2]	26°20'10"	27°20'15"
C2H176Q01	38	Doringdraai Dam Welverdiend	Varkenslaagte Spruit [C2]	26°23'18"	27°16'27"
C2H033Q01	39	Doornfontein	Buffelsdoorn Spruit [C2]	26°26'12"	27°19'38"

Factors taken into account in the selection of the sites included:

- the potential for large-scale drinking water use,
- the identification of significant point-source discharges from mines,
- the need to establish, as far as possible, natural background levels.

2.4 Sampling Frequency and Duration

Since, for chronic radiation exposures, it is the cumulative radiation dose that is important, doses to the public are normally integrated over a full year of exposure for the purposes of assessment. The exact yearly dose from environmental radioactivity, which varies over time, particularly in water sources, can only be determined with high frequency monitoring, ideally on a continuous basis. This was, however, not possible in practice due both to analytical capacity constraints and to budgetary constraints. A compromise had to be reached to ensure reasonable accuracy of the estimation of the integrated annual dose. Thus to achieve a reasonable estimate of integrated annual radiation dose, a weekly sampling frequency and a 25 week sampling duration was adopted for the first phase of the study (7 January to 25 June 1997). Preliminary analysis of the data from the first phase of the study showed that significant autocorrelation existed for the radioactivity data gathered at intervals of less than one month (see Appendix 3). This implied that the sampling frequency could be reduced to once a month without a significant loss in the ability to estimate the annual dose with a reasonable degree of accuracy. Thus, during the second phase of the study (July to December 1997), data was gathered on a monthly rather than on a weekly basis.

2.5 Geological and Radiological Characteristics of the Catchment

Because gold mining was established in the Mooi River catchment long before radioactivity measurements were made, it was not possible to establish unequivocally the true natural background level, especially as the natural ground water recharge constitutes a significant proportion of the base flow of the river. Recent gamma ray spectrometric surveys and a large body of radioactivity measurements on geologically similar areas for airborne radiometric mapping of the environmental impact of gold and uranium mining in Gauteng Province, South Africa, were also reported by Coetzee, H, (1995) [10]. The pertinent geological factors are as follows:

- The dolomitic areas (most of the Mooi River catchment is underlain by dolomite) have very low (~10% of crustal average) radio-element contents. These dolomites also constitute the major groundwater source in the area.
- The quartzites and shales in the area tend to be enriched in potassium, uranium and thorium and consequently, the daughter nuclides of uranium and thorium reach levels generally at 1.5-3 times the crustal average.
- The granites tend to contain slightly elevated uranium concentrations and elevated potassium and thorium concentrations.

The highest naturally occurring uranium series activities in the area are found in the gold reefs of the Witwatersrand Supergroup. These, however, are extremely limited in outcrop, generally sub-outcropping below hundreds or thousands of metres of younger cover rocks.

2.6 Variables Measured and Data Collected

2.6.1 Radionuclides

The three natural radioactive decay series of relevance are those headed by the radionuclides uranium-238, uranium-235 and thorium-232. Details of these decay series and an explanation of terms are given in Appendix 2. The radiological variables originally requested from the AEC for analysis were gross alpha activity and the individual activities of uranium-238, radium-226 and thorium-232. The AEC contributed significantly to the study by determining, in addition, gross beta activity and the individual activities of radium-223, radium-224 and uranium-235. During the second phase of the study the number of radiological nuclides measured was increased to include polonium-210, lead-210, thorium-230, thorium-227, uranium-234, and radium-228. This was done in order to clarify uncertainties in the dose

calculated, relating to the non-equilibrium of nuclides with the parent nuclides in the water phase. It was also decided that the protactinium-231 and actinium-227 in the water samples had to be determined on a limited set of samples.

Additional analyses on the last batch of samples were also performed. These analysis included radiological variables on the suspended solids that were left on the filter in the samples.

The use of gross beta measurements for estimating the contributions of beta emitters to the total radiation dose could not be considered, because the measurements were deemed to be unreliable owing to analysis problems caused by the effects of water chemistry. The AEC concurred that the well-established gross beta measurement techniques used by them could not be regarded as suitable for the determination of very low beta activity concentrations in waters characteristic of those sampled in this study. It was accordingly decided not to accept the gross beta data set, but rather to measure those beta emitters likely to contribute significantly to the total ingestion dose, in phase two of the study. Beta emitters measured included lead-210, radium-228, and actininium-227

The methods used for radiological analysis of the samples are given in Appendix 2.

2.6.2 Chemical Variables

Chemical variables, both major inorganic and trace metal constituents, were measured by the IWQS laboratories. The primary reason for collecting chemical variables was to establish whether a relationship could be found between dose and the chemical variables, so as to answer the question as to whether any of the chemical variables could be used as surrogate parameters.

The chemical variables measured were:

a. The following metals (dissolved fraction): aluminium, barium, bismuth, iron, manganese, lead, yttrium and germanium.

b. The following major inorganic determinands: pH, electrical conductivity, total alkalinity, sodium, potassium, calcium, magnesium, ammonium, chloride, fluoride, sulphate, nitrate + nitrite (as N), phosphate as P, and silicate as Si.

The most significant of the chemical variables measured was possibly sulphate, which is formed by the oxidation of pyrite in the mine residue deposits, leading to acidic conditions conducive to the mobilization of some radionuclides into water.

2.6.3 Other Data

Although the radiological data gathered in this study related primarily to radioactivity in the dissolved constituents of the water, limited data were gathered also on radioactivity in the suspended solids. No data on environmental levels of radioactivity in sediments, river banks, vegetation or other possible elements of the human food chain were gathered. Instead, potential radiological impacts from exposure pathways other than drinking water were estimated on an order-of-magnitude basis through the use of screening models.

Other data collected were flow and rainfall data where available. From the very limited river flow and rainfall data that was available for the catchment, no correlation could be established with the radiological data. Unfortunately very few radiation monitoring sites corresponded with flow gauging sites. In the few sites that did correspond, the flow was heavily influenced by man made structures such as dams, weirs, canals and treatment works. This resulted in a highly modified pattern of flow which displayed little or no correlation with radioactivity.

2.6.4 Access to Analytical Data

Analytical results collected during the study can be obtained from the Hydrological Information System (HIS) of the Department of Water Affairs and Forestry. Requests for data from the HIS can be sent directly to:

Directorate: Hydrology
Department of Water Affairs and Forestry
Paterson 536
Private Bag X313
Pretoria 0001
Tel: (012) 338 7500, ask for the Data Supply Section in Directorate: Hydrology
Fax: (012) 326 1488

The official departmental station numbers, provided elsewhere in the report (example C2H073) should be provided with all data requests. Data can be provided in an ASCII format and files can be provided via e-mail.

2.7 Quality Control

A number of actions were taken to address quality control. As a quality control measure, split samples were analyzed by three laboratories, as part of phase two (Appendix 5). These confirmed the accuracy of the radiological analyses.

The AEC conducted the radiometric analyses of the water samples for the study. As a CNS-recognised laboratory, the AEC adopts approved methods and procedures for analysis, and incorporates specific quality control methods. The quality control and validation done by the AEC's Radioanalytical Laboratory is shown in Appendix 6.
Measurements of uranium by both radiochemical and ICP-MS techniques, during the second phase of the study, allowed comparisons to be made as an additional quality control check. The following good correlation for uranium concentration in mg/ℓ was obtained by linear regression from the 98 samples analysed:

$$[U]_{ICP\text{-}MS} = 0{,}993 \times [U]_{Radiochemical} - 0{,}563 \qquad (r^2 = 0{,}906)$$

Thorium-232 was also measured by both techniques in the second phase, but a correlation between the two techniques could not be established because the ICP-MS measurements were frequently at the lower limit of detection and therefore inapplicable.

In natural uranium, the activity ratio between uranium-238 and uranium-235 is 21,719. The following good correlations, between the data for the two isotopes, were obtained by linear regression:

Radiochemical (phase 2), 98 data:	$^{238}U / ^{235}U = 21{,}341 \pm 0{,}115$	$(r^2 = 0{,}996)$
ICP-MS (phase 1), 570 data:	$^{238}U / ^{235}U = 20{,}785 \pm 0{,}030$	$(r^2 = 0{,}999)$
ICP-MS (phase 2), 63 data:	$^{238}U / ^{235}U = 22{,}171 \pm 0{,}571$	$(r^2 = 0{,}860)$

3. BASIC RADIOLOGICAL CONSIDERATIONS

3.1 Exposure from Natural Background Radioactivity and Medical Procedures

Most of the ionizing radiation to which people are exposed comes from sources which are natural features of the environment. These sources include radon gas and its decay products in the atmosphere (originating from natural uranium in soil and rocks), gamma rays from the ground, cosmic rays from outer space, naturally-occurring radioactivity in foodstuffs and drinking water, derived from radionuclides in the soil, as well as inhalation of respirable airborne dust. The total radiation dose received by an individual, from these natural sources, is typically about 2,4 mSv/a (millisieverts per annum), but geological and geographical factors can cause doses from any one of such sources to be elevated by a factor of 10 in high-background regions [3].

In addition to radiation from natural sources, man is exposed to radiation during medical treatment (X-rays, radiotherapy and nuclear medicine). Internationally, average doses to individuals from all medical sources range from 0,07 mSv/a to 1,8 mSv/a [3].

Thus, a typical member of the public will receive, as a matter of course, a radiation dose of between 2,5 and 4,2 mSv/a. In regions with high natural background, doses of 10 mSv/a are not uncommon.

3.2 Exposure Pathways

Exposure of humans, to ionizing radiation, may occur via various routes or 'pathways' that can be grouped simply as:

- exposures to penetrating radiation from sources external to the body, and
- exposures to both penetrating and non-penetrating radiation from radioactive substances taken into the body by ingestion, inhalation, or absorption through the skin.

Exposures from water containing radioactive contaminants essentially occur internally through ingestion, either by direct consumption or indirectly by consumption of animal or vegetable products that have themselves taken up the water.

A detailed study of the potential major ingestion pathways, relevant to the Mooi River catchment, revealed only two pathways with potential for giving rise to significant exposures (Appendix 7).

- direct ingestion resulting from regular and continuous use of the water for drinking purposes, and
- regular consumption of fish obtained from contaminated water bodies.

With respect to the latter, there is very little information on the bioaccumulation rates of radionuclides in local fish species, and international experience shows that bioaccumulation can vary by as much as three orders of magnitude. The fish pathway therefore requires more research, and could not be addressed in the present study. Accordingly, the decision was taken to address only the drinking water pathway in this study.

3.3 Health Effects of Ionizing Radiation

The process of ionization changes atoms and molecules. In cells, such changes may result in damage which, if not adequately repaired, may:

- prevent the cell from surviving or reproducing, or
- result in a viable but modified cell.

The two outcomes have profoundly different implications for the organism as a whole.

In the case of the former, the loss of large numbers of cells in a tissue can result in a loss in tissue function. Such effects are known as deterministic effects, and are characterized by a dose threshold above which the probability of causing harm increases steeply from zero to 100%. Above the threshold, the severity of harm also increases with dose. Threshold doses are generally two or three orders of magnitude above background doses, and deterministic effects are thus only now seen in the case of accidents or as a side effect of medical radiation therapy.

The outcome is very different if the irradiated cell is modified rather than killed. It may then be able to produce a clone of modified daughter cells which, in spite of the highly effective defence mechanisms within the body, may cause, after a prolonged and variable delay, a malignant condition - a cancer. The probability, but not the severity, of the cancer increases with dose. This effect is called stochastic (meaning of random or statistical nature).

Epidemiological studies have shown, with good statistical significance, that this dose-response relationship is linear for accumulated doses of more than about 200 mSv. It is widely assumed that this linear relationship, with certain corrections, holds true also at lower doses, all the way down to zero - that is, there is no dose threshold for stochastic effects. This linear relationship yields, for low doses and dose rates, a nominal probability of fatal

cancer induction of 5 x 10^{-5} per mSv. Due to the high incidence of cancer induced by other carcinogens, it will be difficult, if not impossible, to obtain conclusive epidemiological evidence supporting this linear relationship at low doses. Some evidence suggests the opposite, in that there is actually a beneficial effect.

Stochastic effects can also take the form of hereditary effects which may be of many different kinds and severity, and are expressed in the progeny of the exposed person. Although the existence of hereditary effects in man is not in doubt, the risk estimates appear to be so small that it is not surprising that epidemiology has not yet detected hereditary effects of radiation in humans with a statistically significant degree of confidence.

Notwithstanding the fact that there is no evidence of statistically significant health effects associated with exposure to low levels of radiation, the internationally accepted principle is to keep radiation exposures as low as reasonably achievable.

3.4 Radiation Protection Principles and the System of Radiation Protection

Internationally a system of radiation protection has been agreed upon, based on the health effects described in section 3.3. This system has been recommended by the International Commission on Radiological Protection (ICRP), which is a non-governmental scientific organization that has been publishing this and related recommendations for over half a century. Different countries evaluate and implement the recommendations in a manner that is appropriate to their circumstances.

The following recommendations of the ICRP [4] are based on the assumption that there is indeed a linear non-threshold relationship between radiation dose and the probability of contracting cancer. Central to the system of radiation protection for proposed and continuing human activities that increase exposure to radiation are the following general principles:

1. No activity, which results in the exposure of persons to radiation, should be adopted unless the activity produces a net positive benefit.
2. All radiation doses should be kept as low as reasonably achievable (ALARA), taking economic and social factors into account.
3. The radiation doses should not exceed limits recommended by the ICRP.

For situations where the sources of exposure are already in place and radiation protection has to be considered retrospectively, remedial action to reduce the exposures should be based on the following general principles:

a) The remedial action should be justified in the sense that the costs, including social costs, should be more than offset by the reduction in radiation dose likely to be achieved.

b) The form, scale and duration of the remedial action should be optimized so that the net benefit to society is maximized.

To apply the above principles to, for instance, radioactivity in water, it is necessary to calculate the radiation doses which result from the use of the water.

3.5 Calculation of Dose for the Drinking Water Ingestion Pathway

The annual radiation dose from any given radionuclide and for any given age group is expressed as:

Annual dose (mSv/a)	=	Activity concentration (Bq/ℓ)	X	Annual consumption (ℓ/a)	X	Dose Conversion Factor (mSv/Bq)

The total radiation dose for that age group is, then, the sum of the doses from individual radionuclides. This implies that the activity concentration of every radionuclide must be known. However, it was not feasible to measure every radionuclide, and this had to be taken into account in the calculation of age group specific doses. The method used to calculate lifetime average doses doses in this report is given in Appendix 8.

Two methods (IWQS and AEC) are presented in the Appendices for calculating the dose. Both need to address the problem that fewer nuclides were measured in the first phase than in the second. The so-called IWQS method handled this problem in two ways :-

1. Where a suitable set of predictor variables (chemical or radioactive) could be found, the missing nuclides were regressed onto a set of predictor variables. The multilinear regression was used to predict what the value of the nuclide was during the first phase.
2. Where no set of predictor variables could be found that performed better than just using the average, the average value was used.

The so called AEC method handled this problem by regressing, for the period of Phase II, those nuclides measured in Phase I onto the dose calculated from all the nuclides measured in Phase II. This regression was used to predict the dose for Phase I. The IWQS and AEC methods differed in the assumptions used of how to deal with unmeasured nuclides.

The second problem that needed to be addressed by both methods was the fact that even in Phase II, not all the nuclides in the decay chains were measured. The so-called IWQS method took a simpler approach to this for the purpose of estimating the uncertainty in the dose arising from not measuring these nuclides. The IWQS method simply assumed that all the unmeasured nuclides had the same value. This implied that the uncertainty remaining in the dose due to the unmeasured nuclides was about 0,003 mSv/a. The AEC method had a more advanced model, based on which nuclide was related to which other via a decay chain of the shortest half-life.

3.5.1 Dose Conversion Factor

Each of the radionuclides in the three decay chains of interest has its own 'dose conversion factor' (DCF) for the ingestion pathway, relating the dose received, in mSv, to the amount of radioactivity ingested, in Bq (becquerels, or number of nuclear disintegrations per second). The DCFs used are those published by the International Atomic Energy Agency (IAEA) [5]. The IAEA gives different dose conversion factors for the various age groups. There are various ways in which the exposure dose per year for the various age groups can be combined. Investigation into the possible ways in which to combine the age groups specific doses showed that differences for the various ways of determining lifetime exposure were in fact trivial, and a "lifetime average" method was adopted for the purposes of this study.

3.5.2 Activity Concentration

In many solid materials such as rocks and soil, the mobility of the elements in the decay chains is limited, even over long periods of time, and the mixture of radionuclides is therefore relatively undisturbed. In such cases, the radionuclides may be said to be in secular equilibrium, meaning that all the radionuclides in a given decay chain have similar activity concentrations.

In water systems, however, the dissolution and precipitation characteristics of the various decay chain elements may differ significantly, leading to a high degree of disequilibrium. Assumptions of equilibrium are, therefore, no longer valid. On the other hand, measurement of the activity concentration of every single radionuclide is neither economically feasible nor necessary in order to obtain a reasonable estimate of the ingestion dose. Certain radionuclides will contribute very little to the overall radiation dose because they have very small DCFs and / or their parents may be present only at very low activity concentrations.

In the first phase of the study, the parent radionuclides of the three decay series, plus the three radium isotopes radium-226, radium-223 and radium-224 that occur near the mid-points

of each series, were measured. In addition, uranium-234 was assumed to be in equilibrium with uranium-238 on the basis of results from other studies [6]. From the results of this first phase, it was established that only three radionuclides of major importance remained unaccounted for: thorium-230, lead-210 and polonium-210. These were measured in phase 2 of the study, together with three radionuclides of lesser importance: actinium-227, protactinium-231 and radium-228, and, therefore, made it possible to calculate the estimated annual dose with a high degree of certainty.

Consideration was initially given to the use of gross alpha measurements for estimating the dose contributions from the radionuclides that were not individually measured. In practice, however, the uncertainties inherent in the determination of gross alpha activity, typically around 20% to 30%, lead to unacceptably large uncertainties in the final dose determination.

The use of gross beta measurements for estimating the contributions of beta emitters to the total radiation dose could not be considered, because the measurements were deemed to be unreliable owing to elevation of the beta measurements caused by water chemistry. The AEC concurred that the well-established gross beta measurement techniques used by them could not be regarded as suitable for the determination of the very low beta levels in the waters characteristic of those sampled in this study. It was accordingly decided not to use the gross beta data in dose calculation, but rather to directly measure the more important beta emitters, with the highest dose conversion factors during the second phase of the study.

4. DRINKING WATER QUALITY CONSIDERATIONS

From the preliminary screening surveys [1,2] uranium was found to be the main radioactive element present, and has both a potential for a chemical toxicity and a radiological hazard. Current DWAF Water Quality Guidelines [7] give criteria for uranium-238 concentrations in drinking water. These criteria are based on the chemical toxicity of uranium to the kidney rather than its radiological toxicity.

From a radiological perspective, it is the total radiation dose from all radionuclides in the water that is important, and the Technical Committee has proposed interim guidelines in this regard, taking into account the following:

(i) The World Health Organization (WHO) recommends a reference level for radiation dose, received from the continuous consumption of drinking water for a full year, of 0,1 mSv/a [8]. This value is only about 5% of the dose from the total natural background, and can therefore be regarded as an ideal situation. From section 3.3 it can be deduced that, on the conservative basis of the linear non-threshold theory, a radiation dose of 0,1 mSv/a represents a probability of attributable fatal cancer of 4 in 10 000 over a 70 year lifetime. By contrast, cancer from all causes is responsible for about 2 000 in 10 000 deaths, it thus being evident that, for the WHO reference level of 0,1 mSv/a, the increase in the probability of cancer induction, if it exists at all, is insignificantly small.

(ii) The dose limit to members of the public due to all anthropogenic sources is currently recommended internationally at 1 mSv/a [4,5], and this has been implemented in several countries. This value is based on acceptance of the linear non-threshold theory, and can therefore be regarded as conservative.

(iii) The dose limit for members of the public, recommended internationally, was previously 5 mSv/a, and many countries still adopt this limit. It is common practice in uranium mining remedial action programmes to design the programmes such that compliance with the 5 mSv/a limit is achieved in the short term, and with the 1 mSv/a limit in the longer term.

(iv) Dose limits to members of the public relate to the combined effect of all exposures from human activities. It is common practice to place a dose constraint on releases from individual facilities. Such a constraint is normally set at some fraction of the dose limit of 1mSv/a - commonly of the order of 0,25 mSv/a, i.e., allowing for the combined dose from up to four separate facilities on a single individual not exceeding the 1mSv/a limit. Although this approach is intended for new rather than existing operations, it may have some relevance to water systems in gold mining areas in that

it embodies the concept of allowing for doses from other sources of exposure without causing the 1 mSv/a dose limit to be exceeded. The reference value of 0,25 mSv/a is the dose limit already imposed by the CNS on individual mines in the Mooi River catchment.

Table 2 gives information on the DWAF guidelines for uranium, while Table 3 embodies the proposed guidelines on radiation dose in drinking water. The DWAF guidelines have taken into consideration all the above limits for the protection of the public from anthropogenic sources of radiation.

The basis for the colour coded classification system was chosen to be in line with the approach used in the joint Assessment Guide, published by DWAF, the Department of Health, and the Water Research Commission [9]. The meaning of the colour classes for chemical constituents given in this DWAF/DOH/WRC guide are as follows:

- **Blue, class 0 = Ideal water quality. Suitable for lifetime use.**
- **Green, class I = Good water quality. Suitable for use, rare instances of negative effects.**
- **Yellow, class II = Marginal water quality. Conditionally acceptable. Negative effects may occur in some sensitive groups.**
- **Red, class III = Poor water quality. Unsuitable for use without treatment. Chronic effects may occur.**
- **Purple, class IV = Dangerous water quality. Totally unsuitable for use. Acute effects may occur.**

The practical meaning intended for interpretation of the classes is that “blue” or “green” water is fit for lifetime use without any further questions. Yellow class or marginal water, is however, only fit for interim use, and should not be used for a lifetime if at all possible. Red and purple class water are seen as unfit for use.

Table 2: Current DWAF 1996 guideline [7] on uranium-238 in domestic water, with colour classes

Uranium-238 (Bq/ℓ)	Uranium-238 (mg/ℓ)	Effects	Colour Class
Target water quality range 0 to 0,89 Bq/ℓ	Target water quality range 0 to 0,070 mg/ℓ	No significant effects. Annual cancer risk less than 1 in 4 000 000.	Blue, Ideal(<0,25 Bq/ℓ) and Green (0,25 to 0,89 Bq/ℓ)
0,89 to 3,6	0,070 to 0,284*	Annual cancer risk less than 1 in 1 000 000. May potentially be a slight risk of renal toxicity in sensitive individuals where renal function is impaired, but unlikely to have demonstrable renal toxicity in healthy individuals.	Yellow
3,6 to 18	0,284 to 1,42	Annual cancer risk less than 1 in 200 000, but significant risk of chemical toxicity with renal damage.	Red
>18	>1,42	Increasing cancer risk in long term. Increasing risk of renal damage in short term.	Purple

* If 0,284 mg/ℓ is exceeded, human health may be at risk due to chemical toxicity.

Table 3: Proposed interim water quality guidelines for the radiation dose in drinking water

Radiation dose (mSv/a)	Suitability	Action required	Colour Class
≤ 0,1 (WHO reference level)	Ideal, suitable for lifetime use	Water complies fully with radioactivity guideline. No further action necessary	Blue (ideal)
>0,1 and ≤ 0,25	Water acceptable for lifetime use, subject to confirmation of dose.	Confirm dose level in respect of specific nuclide analysis	Green (acceptable for lifetime use).
>0,25 and ≤1	Water acceptable for short term use. Use in longer term (lifetime) requires further investigation.	An environmental impact assessment may be necessitated	Yellow (acceptable for short term use)
>1 and ≤ 5	Unacceptable for lifetime use	Remediation required over a reasonable time period.	Red (Unacceptable for lifetime use)
>5	Unacceptable even for short term use	Immediate remediation required	Purple (Unacceptable even for short term use).

5. DISCUSSION OF RESULTS

5.1 Annual Doses within the Mooi River Catchment for the Drinking Water Exposure Route

The annual doses for the drinking water route of consumption, for the Mooi River Catchment, are shown in Table 4 and Figure 3.

Table 4: Final annual total dose [a] in mSv/a for the drinking water route, in the Mooi River catchment, arranged according to ascending dose. Also given is the incremental dose [b] above the estimated background of 0,02 mSv/a.

Site No	Dose[a]	Dose[b]		Site No	Dose[a]	Dose[b]
29	0,02	0,00		16	0,04	0,02
30	0,02	0,00		13	0,04	0,02
14	0,02	0,00		3	0,05	0,03
35	0,02	0,00		10	0,06	0,04
27	0,02	0,00		4	0,06	0,04
34	0,02	0,00		2	0,06	0,04
6	0,02	0,00		39	0,06	0,04
31	0,03	0,01		5	0,06	0,04
26	0,03	0,01		23	0,08	0,06
20	0,03	0,01		37	0,08	0,06
25	0,03	0,01		8	0,08	0,06
28	0,03	0,01		17	0,08	0,06
32	0,03	0,01		9	0,11	0,09
19	0,03	0,01		11	0,14	0,12
33	0,03	0,01		7	0,16	0,14
22	0,03	0,01		15	0,18	0,16
18	0,03	0,01		1	0,24	0,22
24	0,03	0,01		7a	0,27	0,25
21	0,03	0,01		12	0,52	0,50
6a	0,03	0,01				
36	0,03	0,01				
38	0,03	0,01				

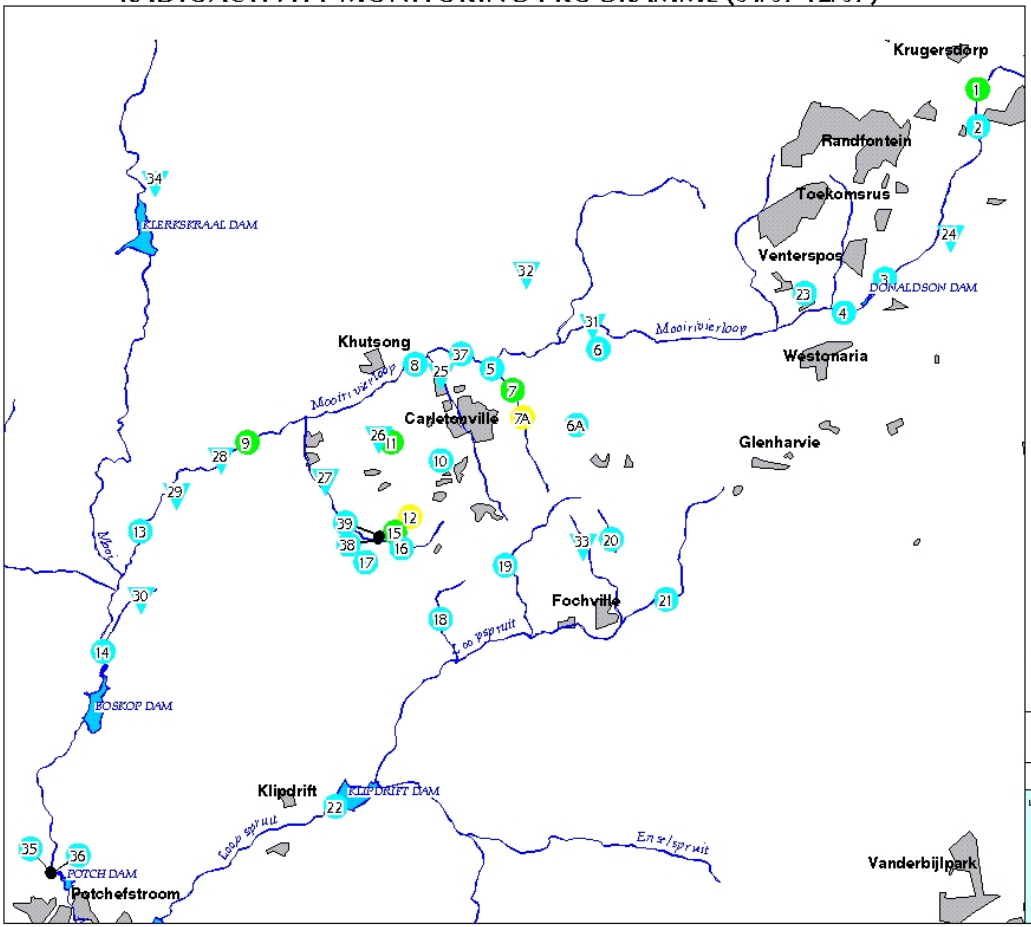
Applying the proposed interim water quality guidelines to the mean annual doses calculated for the radionuclides, an annual dose map for drinking water was produced. The dose map (Figure 3) shows that the radiological quality of the water, at the majority of the sampling sites in the Mooi River Catchment, is either in the ideal (blue, ≤0,1 mSv/year) or acceptable for lifetime use (green; >0,1 to ≤0,25 mSv/year) class.

Two sites were in the yellow class (>0,25 to ≤1,0 mSv/year), implying suitability for interim use, including the need to establish the origin, and consumption rate of the water at the site. No sites were in the red class (>1,0 mSv/year), implying that there were no sites which were unsuitable for use, and thus which needed active intervention.

In summary the following may be stated:

- All sites had an associated annual radiation dose less than 1 mSv/year, implying that at no site was the radiation dose at a level that would necessitate consideration of immediate intervention, such as the necessity of immediately providing an alternative water supply.
- Two sites had a radiation dose level in the yellow class of >0,25 to ≤1 mSv/year. These were:
- Site 7a (West Driefontein mine process water before settling dams). This implies that the water is radiologically suitable for drinking water use for an interim period, but that a site specific investigation should be done, including the collection of information on drinking water consumption.

RADIOACTIVITY MONITORING PROGRAMME (01/97-12/97)



MOOI RIVER CATCHMENT (WONDERFONTEINSPRUIT)

Figure 3:
Annual Dose map

- Towns
- Rivers and Dams
- Surface Water
- Ground Water
- Class 0 — Dose <= 0.100 mSv/year
- Class I — Dose 0.100 to 0.250 mSv/year
- Class II — Dose 0.250 to 1 mSv/year
- Class III — Dose 1 to 5 mSv/year
- Class IV — Dose > 5 mSv/year

Classification: Refer to section 3.4 for assumptions

0 4 8 12 16 20 km

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April 1999

- Site 12 (Doornfontein gold mine service water). It was determined that this site dried up, and that water was no longer being discharged. The radionuclide input to the surface water from this site ceased for the further duration of the 1997 monitoring survey.
- Five of the sites were in the green class (acceptable for lifetime use), with radiation dose levels between >0,1 and ≤0,25 mSv/year.
- The large majority of the sites monitored (34 sites) had insignificant radiation dose levels, and complied fully with the World Health Organization's ideal screening guideline for radioactivity in drinking water of ≤0,1 mSv/year. With respect to those sites at which there was no radiation problem from a drinking water point of view, it was noteworthy that such sites included:
  - (i) The two raw water intakes for drinking water treatment to the town of Potchefstroom.
  - (ii) Most of the groundwater sites, including the Gerhardminnebron, and the Turffontein eye.
  - (iii) The drinking water supply borehole of Welverdiend in the municipality of Carletonville.
  - (iv) All but two of the mine water discharge points.

5.2 Discussion of Predominance of Uranium

The results of the monitoring in the Mooi River catchment have shown that of the radionuclides measured, the parent radioactive element uranium, is responsible for the major portion of the measured alpha activity.

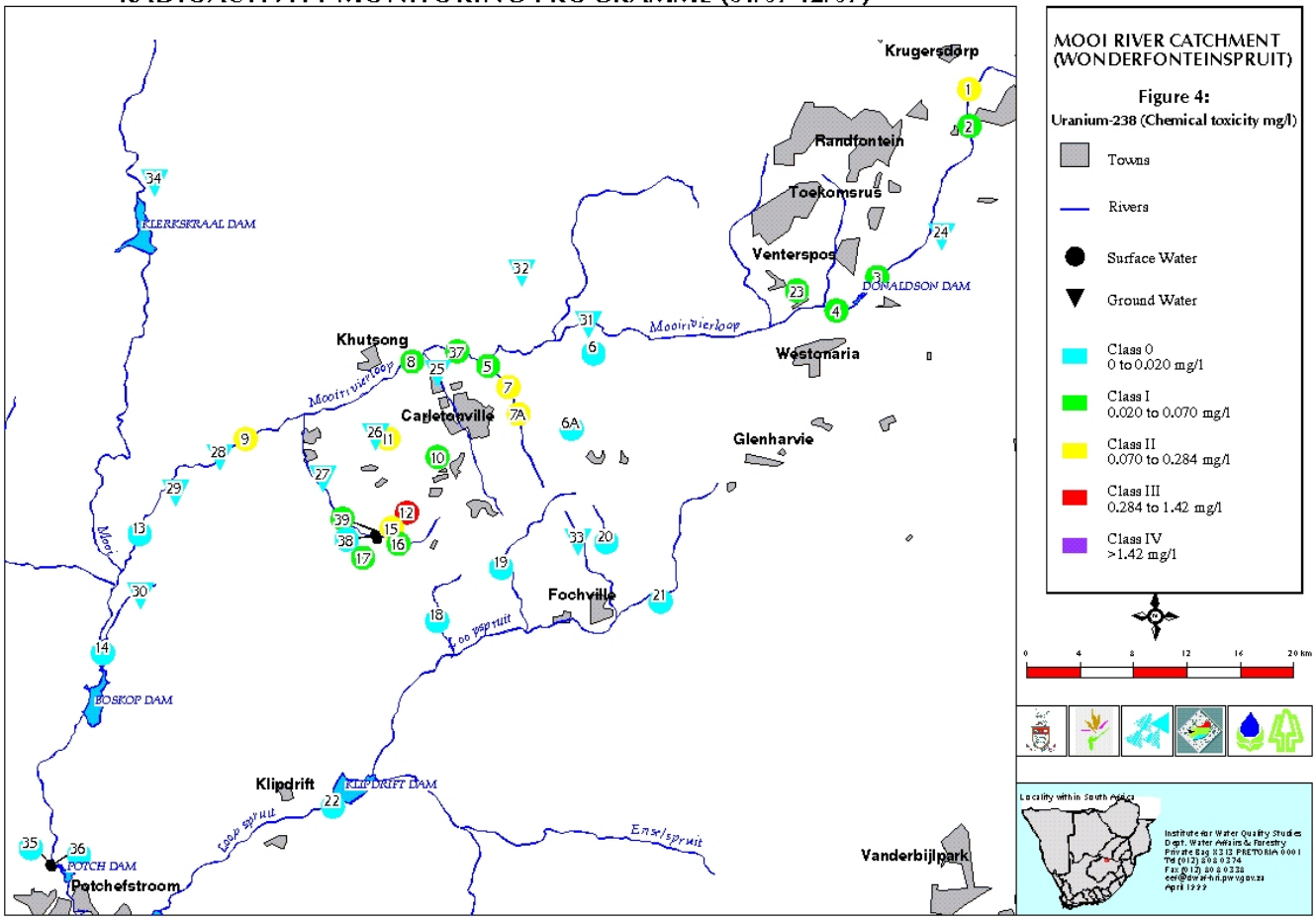
A map representing the measured uranium-238 chemical toxicity values is given in Figure 4, with the proposed colour classes. It can be seen immediately from this map that at the lower end of the catchment the sites are all in the ideal (blue) class, and that specifically the water of Potchefstroom is in the ideal class. The great majority of the sampling sites in the catchment were acceptable as far as uranium is concerned, with only 7 sites requiring further investigation from the viewpoint of uranium chemical toxicity (6 in the yellow class and 1 in the red class). The six sites in the yellow class for uranium chemical toxicity were:

- Site 1: Luipardsvlei.
- Site 7a: West Driefontein process water.
- Site 7: West Drienfontein transfer water.
- Site 11: Doornfontein Gold plant discharge in canal, upstream Doornfontein
- Site 15: Western Deep levels farm bridge down stream, no 7 Shaft Slimes dam.
- Site 9: Mooirivierloop at Blaubank.

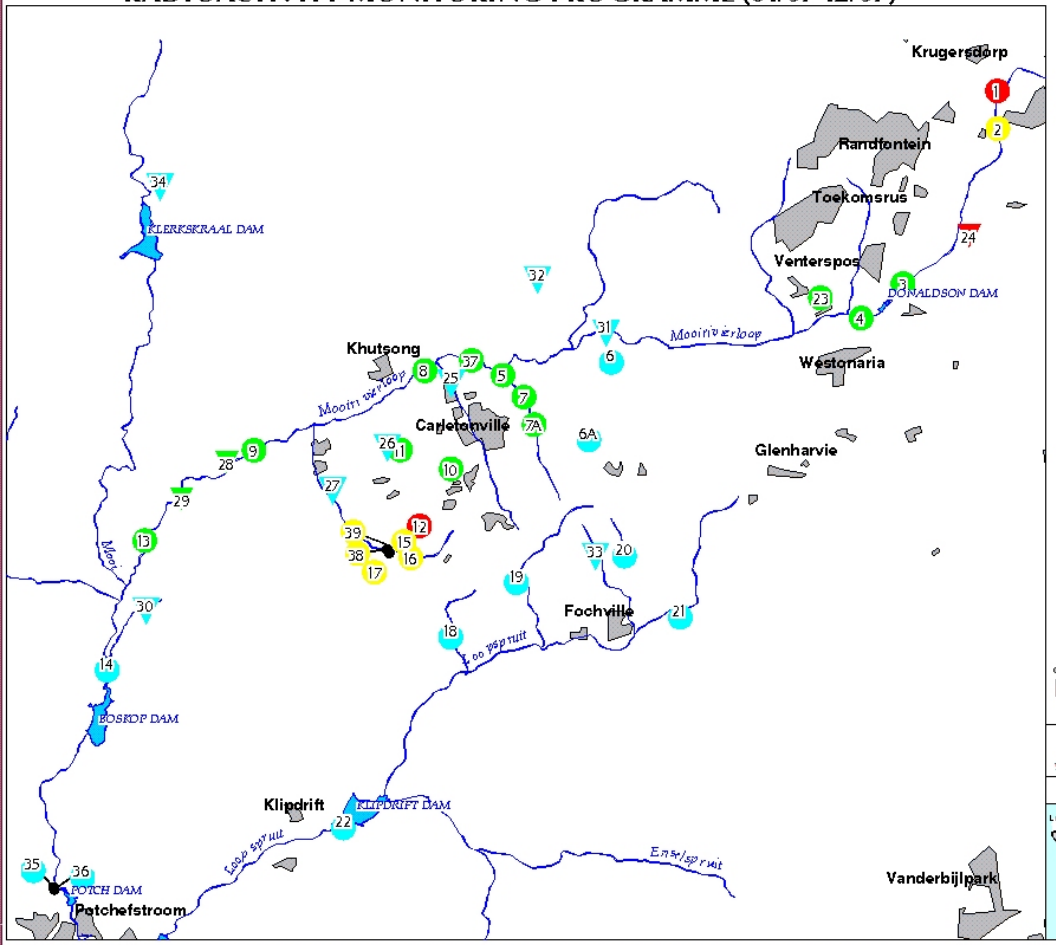
The single site in the red class for uranium chemical toxicity was site 12: Doornfontein Gold Mine no 3 shaft discharge.

It is noticeable from Figure 4, that the majority of sites of elevated uranium concentration occur around the centre of the Mooi River catchment, with the concentrations again decreasing as the river flows further west on course to Boskop Dam. It is debatable what the reasons are for the decrease in uranium concentration after the initial increase around the middle section of the Mooi River. It is noticeable that the sites with elevated uranium concentrations almost all have contributions from mine water. Important attenuating mechanisms downstream of the points of contamination are probably a combination of sediment adsorption and dilution effects.

RADIOACTIVITY MONITORING PROGRAMME (01/97-12/97)



RADIOACTIVITY MONITORING PROGRAMME (01/97-12/97)



MOOI RIVER CATCHMENT (WONDERFONTEINSPRUIT)

Figure 5: Sulphate mg/l

- Towns
- Rivers
- Surface Water
- Ground Water
- Class 0 <= 200 mg/l
- Class I 200 to 400 mg/l
- Class II 400 to 600 mg/l
- Class III 600 to 1000 mg/l
- Class IV > 1000 mg/l

0 4 8 12 16 20 km

Locality within South Africa

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April 1999

The majority of the sites not complying with the chemical drinking water criterion for uranium are associated directly with discharges from gold mining activities.

5.3 Annual Radiation Dose from Background Radiation Levels in Water

The radiation dose arising from the ingestion of the water at the various sampling locations is made up of two components, the dose attributable to background radioactivity in the water and the dose attributable to the additional radioactivity originating from mining activities in the region. As explained in section 2.5, it is not possible to establish unequivocally the background radioactivity levels in the water. However, for some sampling locations the radioactivity levels were very low, and the dose corresponding to these levels was about 0,02 mSv/year. For one of those sampling locations (C2H172Q01, site no. 34), there is no possibility of upstream mining influence. It can be assumed, therefore that a value of 0,02 mSv/year represents an upper bound value for the annual ingestion dose arising from background radioactivity in water.

World wide reference values for non-elevated levels of naturally occurring radionuclides in water [3] correspond to an annual ingestion dose of between 0,01 and 0,02 mSv/year.

It was therefore assumed for the purposes of this investigation that the annual radiation dose attributable to background radioactivity in water was 0,02 mSv/year. It will be seen from the results presented in Table 4 that this value is so small that the uncertainty in its estimation is not critical to the outcome of the investigation.

5.4 Relationship between Uranium Concentration and the Annual Dose

The IWQS (Appendix 8) and AEC (Appendix 9) methods of calculating mean annual dose at each site, while they differed in the assumptions used to deal with unmeasured nuclides, nevertheless gave very similar results, and essentially verified one another.

As shown in Appendices 8 and 9, an excellent linear correlation exists between the annual mean uranium concentration at a site and the annual radiation dose for the drinking water route at that same site. This correlation holds for the Mooi River catchment, but it should be noted that it may not hold equally well for other catchments due to possible differences in radiochemical water quality characteristics.

For all sites in the Mooi River catchment, the following correlation between uranium in $\mu g/\ell$ and the total average annual lifetime dose in mSv/a was found:

$$D = 0{,}0012895\ C_u + 0{,}02128 \qquad (r^2 = 0{,}98)$$

Where D is the annual radiation dose from continuous drinking water use in mSv/year,

And C_u is the uranium concentration in the water in $\mu g/\ell$.

The implication of the existence of this correlation is that for further monitoring purposes in the Mooi River catchment, only the uranium concentration need be measured, from which the all nuclide dose can be accurately estimated. To illustrate the high degree of accuracy with which the total annual radiation dose from drinking water may be estimated from the uranium concentration alone, a comparison of the total dose calculation from the full nuclide analyses (dose[a]) as compared to the all nuclide dose as estimated from the uranium concentration alone (dose[c]) is shown in Table 5.

Table 5: Annual Doses calculated for the Mooi River catchment sites for drinking water. Annual doses [a] in (mSv/a) for drinking water route, in the Mooi River catchment, for the 1997 sampling year arranged according to ascending dose. Also given is the comparative dose obtained from the mean U-238 concentration (mg/ℓ) using the linear regression; dose [c] = 0,0012895 x U + 0,02128 found for the study.

Site no.,	Dose[a]	Dose[c]		Site no.,	Dose[a]	Dose[c]
29	0,02	0,02		16	0,04	0,05
30	0,02	0,02		13	0,04	0,04
14	0,02	0,02		3	0,05	0,07
35	0,02	0,02		10	0,06	0,05
27	0,02	0,02		4	0,06	0,07
34	0,02	0,02		2	0,06	0,05
6	0,02	0,03		39	0,06	0,05
31	0,03	0,02		5	0,06	0,06
26	0,03	0,02		23	0,08	0,05
20	0,03	0,02		37	0,08	0,10
25	0,03	0,02		8	0,08	0,10
28	0,03	0,02		17	0,08	0,10
32	0,03	0,02		9	0,11	0,12
19	0,03	0,02		11	0,14	0,13
33	0,03	0,02		7	0,16	0,18
22	0,03	0,03		15	0,18	0,17
18	0,03	0,03		1	0,24	0,22
24	0,03	0,02		7a	0,27	0,30
21	0,03	0,03		12	0,52	0,50
6a	0,03	0,02				
36	0,03	0,03				
38	0,03	0,04				

5.5 Relationship between Gross Alpha Activity and the Annual Dose

Comparison of the measured gross alpha activity results with the alpha activity calculated from individual radionuclide measurements gave a reasonable linear correlation but with strongly scattered individual data, indicating that individual gross alpha activity measurements should only be used as a screening tool to identify whether the activity is high or low, and not as a decision tool for determining the acceptability of radiological water quality.

The annual radiation dose (calculated from individual radionuclide activities) was found to be linearly related to the annual average gross alpha activity in the following way:

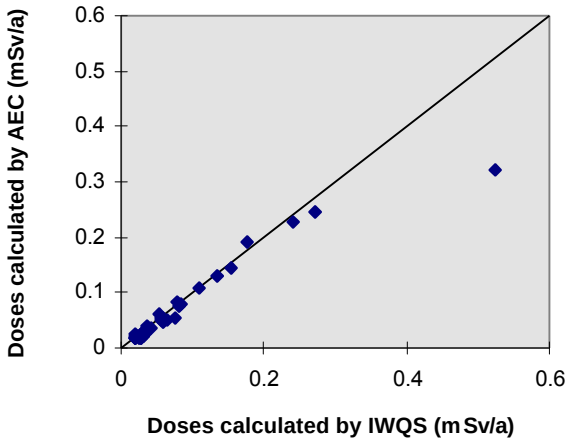
$$D = 0{,}02835\ A_{alpha} + 0{,}021 \qquad (r^2 = 0{,}856)$$

where D is the lifetime average annual radiation dose from continuous drinking water use (mSv/a), and A_{alpha} is the gross alpha activity (Bq/ℓ).

5.6 Verification of Dose Calculations

To verify the doses calculated by the IWQS according to the methodology described in section 3.5 above, the AEC performed an independent dose calculation using, for the unmeasured radionuclides and unsampled sites, different assumptions from those used by the IWQS. Details of the AEC's assumptions and calculation methodology are given in Appendix 8. A comparison of the results from the two calculation methods is shown in Figure 6. It can be seen that, apart from one site (site 12), where the AEC calculation gave a significantly lower dose than the IWQS calculation, the results were in good agreement. The discrepancy with respect to site 12 can be explained by the fact that limited data were obtained from this site, because the flow ceased during the course of the study; in the AEC calculation, 6 months of data were represented by only one data point.

Figure 6: Comparison of doses calculated by the IWQS (method 1) and the AEC (method 2), using different assumptions with respect to the unmeasured radionuclides and sites not sampled in the second phase



The linear relationship between uranium concentration and annual dose, derived using the AEC's assumptions with respect to unmeasured radionuclides and unsampled sites, was:

$$D = 0{,}00124\ C_U + 0{,}017 \qquad (r^2 = 0{,}97)$$

This is very close to the relationship derived using the IWQS assumptions (see section 5.4), as can be seen from Figure 7.

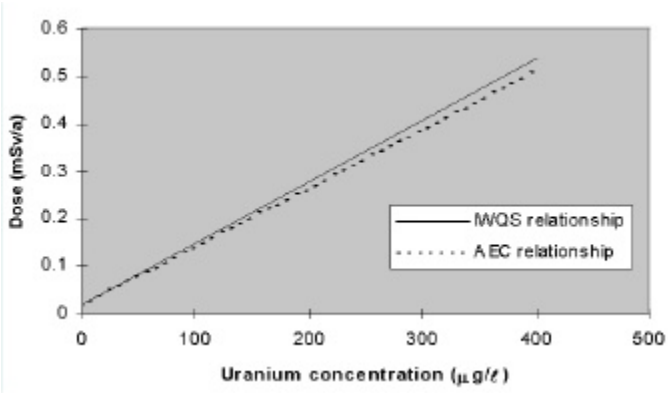


Figure 7: Comparison of IWQS and AEC relationships between uranium concentration and dose, using different assumptions with respect to the unmeasured radionuclides and sites not sampled in the second phase.

5.7 Possible Uncertainties in Dose Calculations

Possible uncertainties in the estimation of the lifetime average annual dose are examined in Appendix 10. The results can be summarized as follows:

- Analytical uncertainties, based on a comparison between the radiochemical and ICP-MS techniques, are estimated to be about 1,5%.
- Uncertainties in projecting the present results to future years, assuming that the variations in radionuclide concentrations observed during the year of study are purely random, are estimated to be typically 20%. If there is a true seasonal component to the variations, then the uncertainty will be less than this value.

- Uncertainties in future dose estimations based only on uranium measurements, arising from the derived linear relationship between uranium and dose, are estimated to be less than 10%.
- Uncertainties due to monthly rather than weekly sampling, based on uranium data obtained in the first phase of the study, were estimated to range up to a factor of 3, but such estimates arise as a result of the short (six month) sampling period. The uncertainties would progressively decrease over longer sampling periods.
- By far the greatest uncertainty is that arising from the assumption of sole continuous use of the water for drinking purposes, which represents a 'worst case' scenario. For an individual falling within any given age group, the dose received will be directly proportional to the amount of water consumed while in that age group.

5.8 Suspended Solids

It was not the intention of this study to measure radioactivity in the solids suspended in the water. However, in order to obtain an indication of the possible contribution of suspended solids to the radiation dose from ingestion, concentrations of individual alpha-emitting radionuclides in the suspended solids were measured in samples obtained from the 15 sites sampled in the final month of the monitoring programme (December 1997).

In calculating the annual radiation doses from ingestion of the suspended solids, it was assumed that the uptake factors were the same as those for the dissolved constituents. The doses, expressed as percentages of the doses from filtered water, were found to be very low:

Average over 15 sites:	2,3% ± 2,1%
Median:	1,9%
Minimum:	0,1%
Maximum:	7,6%

Contributions to the dose from the suspended solids were found to originate mainly from the radionuclides thorium-230, polonium-210, actinium-227, protactinium-231 and thorium-232. This contrasts with the situation for filtered water, where the main contributors to dose were uranium-238, uranium-234 and radium-226.

5.9 Chemical Results: Sulphate

A summary of the sulphate concentrations found in the study is shown in Figure 5. The reason for collecting chemical data in this study, was to enable correlations with radiological data to be explored. An extensive search was made for meaningful correlations between the radiological variables and the total dose, but no statistically significant meaningful correlations were found.

The correlation between mean annual sulphate concentration and mean annual uranium concentration was investigated, but found to be poor (r^2 = 0,394). This implies that sulphate levels can, therefore, not be used as a surrogate for indicating the possible presence of radioactivity. Sulphate in water is, however, important from the viewpoint of drinking water in that it gives rise to traveller's diarrhoea in individuals not used to drinking high levels of sulphate. Sulphate also accelerates corrosion in distribution systems and appliances.

6. The Gauteng Regional Office Water Quality Management Strategy for the Mooi River

6.1 Source Directed Controls

The Gauteng Regional Office has for some time identified the need to control, monitor and audit all point sources in the Mooi River catchment more effectively. The method used is to instruct all direct impactors to complete a strategic water management plan to ensure their effective management of the activities total water balance. The water quality management plans should include, amongst other aspects, the following:

- Water quality management measures in order to minimise pollution should be implemented at source. The fundamental principle is to prevent, inhibit, retard or stop the hydrological, chemical, microbiological, radioactive or thermodynamic processes, which result in the contamination of the water environment.

- If the water/waste water problems cannot be solved by the above water quality management measures at source, water/waste water reuse and minimisation measures should be implemented. This includes the prevention of the inflow of ground and surface water into the industry and mining related activities.

- If the water/waste water problems cannot be solved by reuse and minimisation measures, then water/waste water treatment applications should be implemented.

It should be appreciated that all of the above entails intensive negotiations between the relevant role players including catchment forums, consultants and specialists where necessary. This ensures participation, collaboration and transparency in decision making.

6.2 Water User Assessments

To assess the extent of water use in the catchment, impactors were requested to initiate, in collaboration with the Region, water user assessments in the catchment. The results are captured in Appendix 1.

6.3 Actions taken at Sites 7a and 12

The application of water quality management measures has resulted in specific actions being taken to address the sites showing elevated levels of radioactivity. These are as follows:

- West Driefontein Gold Mine (Site 7a)

The source of the water at Site 7a is excess mine water which is a mixture of recycled underground water, stormwater and final sewage effluent. The mine is currently investigating all options to control at source, reuse and minimise their excess water. This investigation includes the quantification of their total impact on the water environment.

- Doornfontein Gold Mine (Site 12)

The source of the water at Site 12 is excess mine water which is a mixture of recycled underground water and fissure water. The mine has investigated all options to control at source, reuse and minimise their excess water. This investigation included the quantification of their total impact on the water environment. The permit application was lodged at Department of Water Affairs and Forestry in December 1998.

Both these sites have been identified as currently not posing a threat for use as drinking water in the short term. Further investigation will be required to establish whether the water quality is radiologically acceptable in the long term.

6.4 Monitoring

As part of their functions in the catchment the Gauteng Region undertakes river and audit monitoring at point sources. The analysis of chemical uranium at specifically identified sites was initiated during phase 1 of the study. Following phase 1 of the study the routine monitoring program has been extended to include the sites of elevated activity.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 General Conclusions

The aim of the radioactivity monitoring programme in the Mooi River was to address the risk of radioactivity in water to human health, and to determine the total dose from surface and some ground water sources that are, or could be, used potentially as drinking water supplies. After a year of data collection, the results showed that of the 41 monitoring sites covered by the study, 39 sites exhibited a water quality that is ideal or acceptable for continuous lifetime use in terms of proposed interim water quality guidelines for radioactivity in drinking water. At the two remaining sites, both of which are associated with the discharge of water from gold mining activities, the elevation of radionuclides is such that the water is still radiologically acceptable for use as drinking water in the short term, but further investigation would be required to establish whether the water quality is radiologically acceptable in the longer term. It should be noted that at no site was the radiological quality such that immediate remediation was called for.

7.2 Municipal Water Supplies

The only water in the Mooi River catchment used as a source of municipal drinking water is that supplied to Potchefstroom from the Mooi River and the ground water supplied to Welverdiend in the municipality of Carletonville. In both cases, there was no significant elevation of radioactivity above background levels, and the water falls into the 'ideal' classification in terms of proposed interim water quality guidelines for radioactivity in drinking water.

7.3 Indicators of Radiological Water Quality

The search for simple indicators of radiological quality revealed the following:

(a) Some correlation exists between annual mean gross alpha activity and annual radiation dose from ingestion, but is not particularly strong.

(b) The correlation between gross beta activity and radiation dose is poor.

(c) Although waters with elevated radioactivity levels generally exhibit elevated sulphate concentrations, the converse is not always true. Consequently, sulphate concentration is not a reliable indicator of radiological water quality.

(d) An excellent linear correlation exists between annual mean uranium concentration and the annual radiation dose from ingestion. The best-fit linear relationship for the data gathered in this study is given by:

$$D = 0{,}0012895\ C_U + 0{,}02128 \qquad (r^2 = 0{,}98)$$

where: D = average lifetime annual radiation dose from continuous drinking water use (mSv/a)

C_U = uranium concentration in the water ($\mu g/\ell$)

The estimated uncertainty arising from the use of this relationship to predict annual radiation doses arising from the use of waters in the Mooi River catchment for continuous drinking purposes is less than 10%.

It remains to be seen at this stage whether different relationships will apply to different catchments or whether a single, more general relationship can be established that will be applicable across several catchments. The validity of the correlation between total dose and uranium concentration for the Mooi River catchment should be checked periodically where used for long term monitoring.

7.4 Suspended Solids

Preliminary indications were that the additional radiation dose resulting from the ingestion of the suspended solids in the water is minimal (≈2% on average) and can therefore be ignored.

7.5 Guideline Development

Provisional guidelines for evaluating the significance of the drinking water pathway of radiation exposure were developed, based on a synthesis of the dose limits given by the World Health Organisation, the Council for Nuclear Safety, and the IAEA recommendations.

7.6 Recommendations

The following recommendations can be made from the results of the study:

(i) Action

No immediate action is required to reduce radioactivity levels in surface and ground waters in the Mooi River catchment.

(ii) Management approach

The future monitoring and control of radioactivity in surface and ground waters should be integrated into the existing approach used in the management of the catchment, in terms of which all pollutants of concern are addressed.

(iii) Application of relevant International Commission on Radiation Protection (ICRP) principles

The ongoing regulation, at source, of intended radioactive discharges from mining operations affecting water quality in the catchment should be conducted in accordance with relevant ICRP principles, which are as follows:

Firstly, radiation doses should be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account. This should involve a periodic review of existing practices to see that they conform to the ALARA principle.

Secondly, the exposure of individuals should not exceed 1 mSv in a year, taking into account other radiation sources subject to control. To enable regulation to be applied at source, this will require that the optimization of protection according to the ALARA principle be constrained by source-related dose constraints of less than 1 mSv in a year. Discharges of radioactivity in water should accordingly be subject to appropriate limitation on a mine-specific basis.

(iv) Monitoring strategy

The experience and knowledge gained in this study should be used as input to the formulation of a national strategy and action plan for routine and follow-up monitoring of radioactivity in public water streams, as part of an integrated approach to water quality management. The principal approach to radioactivity monitoring should be as follows:

Where no data exists, then a full nuclide analysis is advisable. For the Mooi River catchment, monitoring of uranium on a monthly basis only may be used, with use of the relationship between uranium and running average annual dose as a monitoring and evaluation tool. Within this catchment, monitoring of chemical uranium concentrations (or surveillance in the absence of water flow) should continue on a monthly basis at those sites associated with radiation doses greater than 0,1 mSv/a (sites 1, 7, 7A, 9, 11, 12 and 15) and at those sites associated with municipal water abstraction (sites 27, 35 and 36), as part of the integrated catchment management

approach referred to in (ii) above. The average uranium concentrations over a year should be used to estimate the annual radiation dose at each site from sole continuous use of the water for drinking purposes, using the relationship derived in this study. Site 12 needs to be kept under surveillance if and when water flow recommences at this point.

(v) Chemical uranium as an indicator

The use of chemical uranium as a monitoring parameter for radioactivity should be investigated for other catchments to determine its applicability outside the Mooi River catchment.

(vi) Mine closure

The potential for ongoing radiological impacts, after mine closure, on water sources in the Mooi River catchment should be taken into account in the site-specific mine decommissioning plans that are required as part of the mines' Environmental Management Programme (EMP) obligations. Such plans address all potential sources of environmental pollution, such as acid mine drainage, in a holistic manner, so that interdependencies are taken into account. Radioactivity should be included in this holistic approach. Decommissioning plans will specify the nature and duration of any aftercare arrangements that might be required, and these will include appropriate ongoing monitoring requirements with respect to chemical and radiological pollutants.

(vii) Radioactivity in sediments

Since this study was concerned only with radioactivity in water sources, the question of radioactivity in the sediments in the Mooi River catchment remains largely unexplored. An investigation of radioactivity in sediments needs to be undertaken, with a view to understanding the role played by water chemistry, and it should be noted that this is indeed the subject of a project funded by the Water Research Commission starting in 1999 (Project No. K5/1095: Tier 1 Risk Assessment of Radionuclides in Selected Sediments of the Mooi River).

(viii) Radionuclides in fish

Because of the huge uncertainties in the uptake of radionuclides in fish, studies on the fish consumption exposure pathway should be conducted. It needs to be established whether potential radiation dose from this route in the first instance is likely to be significant or not.

(ix) Continuation of Technical Committee

The current Technical Committee should continue in order to ensure continuity of the monitoring efforts in catchments other than the Mooi River catchment as part of the national radiological monitoring programme.

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APPENDIX 1

WATER USERS IN THE MOOI RIVER CATCHMENT
GAUTENG REGION
DEPARTMENT OF WATER AFFAIRS AND FORESTRY

Appendix 1

WATER USER ASSESSMENT FOR THE MOOI RIVER CATCHMENT

1. Upstream from the Railway bridge (Point1)

- No water users are present.
- Property belongs to Rand Gold.

2. Between the railway bridge and Azaadville bridge (Between points 1 and 2)

- Possibility exists that children from Kagiso can play in the water.

3. Between the Azaadville bridge and Attenuation dam (Between points 2 and 3)

- Possibility exists that children can play in the water.
- The Municipality (Rietvallei, Lusaka) provides informal settlements with water from Rand Water.

4. Between the Attenuation dam and Doornkop road (Between points 2 and 3)

- Dairy farm: Cattle drink water from the stream.
- Irrigation of vegetables (spinach, carrots and beetroot).
- Workers are provided with water from boreholes and most of the workers stay in Bekkersdal.

5. Donaldson dam (Between point 3 and 4)

- Dam is used for recreation such as swimming and fishing.
- Permanent residents get water from the Municipality of Westonaria.
- People from Bekkersdal use the water for religious rituals.
- A new informal settlement upstream of Donaldson dam may use water for domestic purposes.

6. Moses's borehole (point 24)

- Water is used for irrigation of vegetables.
- REGM is currently supplying the people with water for domestic use.
- Please note that other people in the area are using boreholes.

7. Between Donaldson dam and beginning of 1m pipeline (Between point 3 and 4)

- Water could be used for domestic use such as washing of clothes and bathing.
- No information on water used for drinking purposes.
- Children can swim at this point.

8. Venterspost (Point 23)

- Water pumped from underground is used in the process.

9. Beginning of the 1m pipeline – end of 1m pipeline (Between point 4 and 5)

- Ten people at an old school extract water from the pipeline for domestic purposes.
- Water is used for cattle.

10. End of 1m pipeline (Point 5 and between 5 and 7)

- People live next to the canal that conveys process water from West Driefontein Gold Mine.
- These people use fissure water from the Bank Canal for household purposes.

- Approximately 150 people (60 adults and 90 children).
- Fish are caught in both the process and the fissure water canals (this is not their only source of protein).
- Children play and swim in the canals in summer.
- Mr. Jaap Greyling rents the property.
- Far West Rand Dolomitic Association provides the workers with water.

11. Stock Theft unit (point 32)

- Borehole is used for domestic use.
- Only source of water.
- Water is not used for cattle and irrigation of crops.

12. Toxopeus (Point 31)

- Borehole water is used in the piggery and for domestic purposes.

13. End of 1m pipeline- Harry's dam (Between point 5 and 8/ Point 7-8)

- At Harry's dam a family of 15 people (ten adults and five children) use the water from the dam as their only source of water for domestic purposes such as drinking, washing of clothes and bathing.
- Vegetables for own consumption are irrigated with the water (this is not their only source of vegetables).
- Fish are caught in the dam (this is not their only source of protein).
- Children play downstream of the dam in the water.
- Auction grounds are situated next to the dam where cattle are sold. The cattle that are brought, but not removed from the premises are allowed to graze next to the river and dam.

14. Between Harry's dam and Abe Bailey (Between points 5-8/ 7-8)

- Horse stables

  - Approximately 50 people stay on the premises.
  - The owner of the stables provides workers at the stables with water from the Carletonville Municipality on a daily basis. (Provides them with 2 X 25l drums of water for drinking purposes).
  - Water from the canal is used for the horses and other domestic purposes such as bathing and washing of clothes.
  - Water from the canal can be used if no other water is available for drinking and cooking purposes.
  - Three/ four fish are caught weekly (this is not the only source of protein),
  - Horses are the only animals who use the water.
  - A doctor suspected that the water was responsible for one of the workers being sick (it is not known what was wrong with the person).

- Mooitooi Nursery (Between point 5 and 7)

  - Mr. Jacobs provides his family and workers with borehole water for all domestic purposes.
  - Water is also used to irrigate the plants.

- Dairy (Between points 5-8/ 7-8)

  - The Far West Rand Dolomitic Association supplies the farmer with water from Rand Water for domestic purposes.
  - Cattle are provided with water in troughs and cannot reach the canals.

- Montrose farm (Between points 5-8/ 7-8)

  - Ten adults and four children.
  - The workers are provided with water from boreholes or Rand Water for domestic purposes including drinking, bathing and cooking).
  - Canals are used for fishing, washing of clothes and the water used for growing vegetables.
  - Children are not allowed to play in the canals since 3 children were washed away by the water.

- Second set of houses on the farm (Between points 5-8/ 7-8)

  - Two adults and three children.
  - Water from boreholes and Rand Water is used for domestic purposes.
  - Water in the canal is used for washing of clothes.
  - No fish were caught for the last couple of months.
  - A remark was made that no vegetables were grown because of the water.

- Houses between Offices and the Midstream Canal (Between points 5-8/ 7-8)

  - Six adults and four children.
  - Montrose farm provides water for domestic use.
  - Water in the Wonderfonteinspruit is used for the washing of clothes.
  - Children are not allowed to play in the canals.
  - No crops are irrigated.

- Montrose Offices (Between points 5-8/ 7-8)

  - No vegetables are currently grown.
  - Water from Rand Water is provided to workers.
  - Water tanks provide the workers on the fields with water.

- Lintia piggery

  - Fifty adults and forty eight children
  - People are provided with water from a borehole for domestic use.
  - Pigs are the only animals and are provided with water from the boreholes.
  - People do not fish in the Wonderfonteinspruit.

- Alie du Buys (Dairy) (Between points 5-8/ 7-8)

  - Rand Water is used to provide water to fulfil the needs of the people and the cattle.
  - Cattle could drink the water in the Wonderfonteinspruit if they graze in the vicinity.

- Laubsher (Between points 5-8/ 7-8)

  - Water is provided from Rand Water for domestic use.

- Salie Petoors (Between points 5-8/ 7-8)

  - Animals graze in the vicinity of the Wonderfonteinspruit and have access to the water in the river.
  - The possibility exists that the workers drink the water from the stream

- Modibedi's (Between points 5-8/ 7-8)

  - Approximately 4 families.

- Rand Water is used for domestic purposes.
- People from Khutsong catch fish in the Wonderfonteinspruit.
- Animals are provided with water from Rand Water.
- Animals have access to the river when grazing in the vicinity of the river (17 cattle and 25 sheep).
- Cattle produce 15 litres of milk per day that is divided amongst the families.
- Cattle are not slaughtered.

15. Abe Bailey - Blaaubank

- Abe Bailey Nature Reserve (Point 8)

  - Guests and workers are provided with water from the Municipality.
  - Workers catch fish, mainly carp and barbel on a regular basis but this is not their only source of protein.
  - The river is extensively used for water sport and water activities for children who attend camps at the nature reserve.
  - Water is supplied to various water points for game.

- Shop at Khutsong next to the river (Between points 8-9)

  - The municipality provides workers with water from Rand Water.
  - Goats, cattle and sheep are looked after so that they are not allowed to drink the water from the river.
  - Troughs at the shop provide the animals with water from the municipality.

- Khutsong- Welverdiend road Yellow house next to the road. (Between points 8-9)

  - Twelve adults and three children
  - Water for domestic purposes are received from a farm. Problems are experienced with the availability of the water, therefore water from the stream can be used.
  - Water from the river is used for washing of clothes and bathing.

- Khutsong sewage works. (Between points 8-9)

  - Five adults
  - The municipality provides water for domestic use.
  - Fish are caught on a regular basis for own consumption (4 fish are caught at a time). This is not their only source of protein.
  - These workers stay at the Welverdiend Water Care Works.

- Brick Works

  - Approximately 14 –20 families stay here (between points 8-9).
  - Water from the stream is used for domestic purposes as well as a borehole on the property.
  - Currently problems are experienced with the borehole.
  - Therefore water from the stream is mainly used for domestic purposes.
  - People fish on occasions, but this is not their only source of protein.

- Mr. Douw Pretorius. (Between points 8-9)

  - Mr. Pretorius does not use water from the river.
  - His workers, household and animals are supplied with water from boreholes.
  - Fodder is irrigated with water from a borehole.

- Mr. Erich Stoch

- Mr Stoch's animals have access to the river.
- Complaints have been received on numerous occasions that the water in the river caused his animals to die or become ill.

- Welverdiend Sewage Works

  - Workers regularly catch fish.
  - Water for domestic purposes is supplied by the Municipality of Carletonville.

- Paddadam (Between points 8-9)

  - A survey was done on the weekend of 10/5/97.
  - Approximately 20 people visited the dam on this day.
  - Fifty percent of the people catch fish on a regular basis at the dam.
  - Main species of fish caught at this dam include carp, barbel and bass, average weight 2-10 kg.
  - The fish are used for their own consumption or sold to the local people from Khutsong.
  - Permanent residents at the dam catch 2-3 fish on a daily basis for their own consumption but this is not their only source of protein.

16. Blaaubank- Muiskraal

- Blaaubank (Point 9)

  - Nine families (26 adults and 14 children).
  - Mr. Coetzee provides the workers with water for domestic use via a water tanker from a borehole.
  - Fish are seldom caught in the river for own consumption.

- Mr. Coezee's farm (Between point 9 and 13)

  - Water is supplied to the workers and his family from boreholes.
  - Fish are seldom caught for own consumption.
  - Approximately 100 ha of maize are irrigated from the river and boreholes.
  - Cattle have access to the river.
  - These cattle are mainly beef cattle and sold on the market in Johannesburg.
  - A few cows provide milk for the owner and the workers.

- Mr. Visser' borehole (Point 28 and between 9 and 13)

  - Mr. Visser and his workers are supplied with water from boreholes for domestic purposes.
  - Workers regularly catch fish for their own consumption. (The fish is not their only source of protein).
  - Maize, used for feeding the cattle, is irrigated with water from the river as well as the boreholes.
  - The cattle have access to the river when they graze in the vicinity.
  - The cattle form part of a stud but are slaughtered on occasions for own consumption.
  - Vegetables for own use are irrigated from the boreholes and the river.

- Turffontein eye (Point 29)

  - Annetjie and Gideon Wiese (Point 29)

    - Water for domestic use is supplied by a borehole on the farm situated 50m from the river.

- The concern was raised that the water in the borehole is the same as that of the river since it is situated close by.
- The pool at the Turffontein eye is used for recreational purposes including fishing and swimming.
- Cattle, goats and sheep have access to the river and the Turffontein eye. The cattle are mainly sold as beefers.
- Until recently Ms. Wiese had farmed with exotic water birds. This was stopped because of the rumour that the water was radioactive and this resulted in eggs that did not hatch.

- Mr. Chris Bezuidenhoud.

  - Boreholes are used to supply the workers, families and school on the farm with water for domestic purposes.
  - Fodder is irrigated from the river for 400 dairy cows.
  - The milk is supplied to Kraaukamp in Randfontein.
  - Water from the eye and river is used for drinking water for the cattle.

- Gerhard Minnebron (Point 30)

  - The eye provides the family with 200 kilo-litres of water per hour for domestic purposes.
  - An angling club has access to the eye to catch trout.
  - Water from the eye is used to irrigate more or less 12 ha of maize for the cattle. Ninety cattle are supplied with water for drinking purposes from the eye and a borehole.
  - The cattle are sold to a local butcher.

17. Bovenste Eye –Boskopdam

- The Bovenste eye of the Mooi River (Point 34)

  - Three adults and 3-4 children.
  - Water from the eye is used for all domestic purposes.
  - Cattle that graze here belong to Mr Piet Pienaar.
  - They have access to the water in the river.
  - The area is popular for camping or a picnic.

- Klerkskraal dam (Between points 34 and 14)

- Police station

  - Water for domestic purposes is supplied from a borehole.
  - In summer the nature reserve is a popular fishing area.
  - Workers from the Department of Water Affairs and Forestry who look after the canal system have approximately 10 cattle on the property.
  - Water for domestic use and drinking water for the cattle is supplied by a borehole.

- Informal settlement in the area of Rooidraai

  - People from the informal settlement get water from the irrigation canals from the Klerkskraal dam.
  - In the area are approximately 60 farmers who irrigate crops from the canals.

- Welverdiend –Rysmierbult road

  - Farmers in the area have water tanks, windmills, crops and cattle.

- The conclusion can be made that farmers are dependant on boreholes for water for domestic use and irrigate from the river or irrigation canals.
- No intensive investigation was done in this area to identify the users.

18. Varkenslaagtespruit

- Doorndraai dam in the Varkenslaagtespruit.

  - The dam belongs to an angling club and only club members are allowed to fish here.
  - No persons were encountered during the days the survey was done.
  - It is known that a family of 3-5 people stays in the vicinity of the dam.
  - Mr. Jan Nell supplies water to these workers.
  - Mr. Chris Bezuidenhoud rents the farming lands from Doornfontein Gold Mine for grazing lands.

- Deelkraal dam (Point7)

  - People are allowed to catch fish in the dam.
  - However, these fish are not allowed to be removed because of elevated levels of radioactivity in the dam.
  - Notices around the dam prohibit people from removing the fish.

- Elandsrand – Nursery dam (Point 16)

  - Water is supplied by Rand Water for domestic use
  - Twelve cattle are provided with Rand Water water.
  - No fishing by the public is allowed on the property since this is private property.
  - Property belongs to Western Deep Levels.
  - Fodder for the cattle are irrigated from the borehole.

19 Process water canal from West Driefontein (Between points 7A – 7)

- De Freitas Vegetable's stall next to the Carletonville-Potchefstroom road upstream from point 7.

  - Workers in the fields are supplied with drinking water from the Carletonville Municipality.
  - Process water is pumped from West Driefontein no 5 shaft into the Brink dam from where the water is used to irrigate vegetables.
  - Workers that sleep on the property are supplied with water from the Municipality.

- Montrose Grass Enterprises near settling ponds.

  - 100 people work on these lands.
  - Water is supplied from the Montrose offices, as it is required.
  - Industries are approached during the day if drinking water is not available.

- Village where workers from Montrose Grass Enterprises stay (C2H063).

  - Water is supplied from the offices to the workers.
  - Children are not allowed to play in canals.
  - No irrigation is done from the canals.

- Mr. AC van Wyk (downstream of point7)

- Water is supplied by the Far West Rand Dolomitic Association.

- Houses downstream of C2H63

  - People are provided with water from Montrose Enterprises for domestic use.
  - Water in the canal is used for washing of clothes and bathing.
  - Children are not allowed to play in the canals.

APPENDIX 2

METHODS OF ANALYSIS USED BY THE AEC FOR THE RADIOLOGICAL ANALYSIS OF THE SAMPLES

A FAANHOF

ATOMIC ENERGY COMMISSION

Appendix 2

METHODS OF ANALYSIS USED BY THE AEC FOR THE RADIOLOGICAL ANALYSIS OF THE SAMPLES

The analytical method used for gross activity was aeration followed by liquid scintillation counting, with evaporation followed by gas-flow detector counting as an alternative method. The method used for U-234; U-235; U-238; Pa-231; Th-232; Th-230; Th-228; Th-227; Ac-227; Ra-228; Ra-226; Ra-224; Ra-223; Po-210; and Pb-210 was radiochemical separation followed by alpha particle spectrometry; Internal yield tracer and certified efficiency calibration standards. As an additional method U-235, U-238 and Th-232 were also determined by sample atomisation followed by mass determination using chemical calibration standards.

APPENDIX 3

SAMPLING AND INSTITUTE FOR WATER QUALITY STUDIES ANALYTICAL PROCEDURES

Appendix 3

SAMPLING AND INSTITUTE FOR WATER QUALITY STUDIES ANALYTICAL PROCEDURES.

Water samples were collected from each site in the Mooi River with a polyethylene bucket. The bucket was first rinsed with water at the site from which the sample was to be collected. The sample was then collected in one scoop action, from the top 30cm of the water column. Samples from boreholes were collected after the pump on the borehole was allowed to run for at least 2 minutes, to ensure any resident water was removed from the pipes.

The sample containers were then filled from the single bucket of water to ensure split sample collection from the same container. The 5 litre polyethylene radioactivity sample containers were supplied by the Atomic Energy Commission (AEC). The containers were rinsed and then filled to the rim of the bottle.

Samples from each site were numbered according to the unique sampling site number provided in the main report. The date and time of sampling was also written on the sample labels.

No preservatives were added to the samples for radioactivity analysis, and samples were submitted to the AEC within 24 hours of sampling.

Samples for trace metal, major inorganic and turbidity analysis were collected in red, white and green 350 ml polyethylene bottles respectively, supplied and precleaned by the IWQS laboratories. The major inorganic samples were preserved with mercury chloride. All samples were submitted within 24 hours to the IWQS laboratories.

The analytical procedures for the trace metal, major inorganic and turbidity are described in the Analytical Methods Manual, Technical Report 151, Department of Water Affairs and Forestry.

APPENDIX 4

INFORMATION ON DECAY CHAINS
NATURALLY OCCURRING RADIONUCLIDES

Appendix 4

INFORMATION ON DECAY CHAINS

NATURALLY OCCURRING RADIONUCLIDES

Tables A4.1, A4.2 and A4.3 list the radionuclides in each of the three radioactive decay chains of relevance to this study. Every radionuclide, when ingested, gives rise to a radiation dose to the individual. The amount of dose varies by orders of magnitude from one radionuclide to another, as illustrated by the tabulated values of annual dose per unit activity concentration in water. Details of the calculations involved are given in Appendix 8.

Notes on Tables A4.1, A4.2 and A4.3

1. The annual dose per unit activity in water is defined for the purposes of this study as the radiation dose, in millisieverts, received annually by an individual from the sole continuous use of drinking water at two litres per person per day containing 1 becquerel of activity of the radionuclide concerned per litre of water, averaged over a lifetime of 70 years.

2. (1 becquerel = 1 nuclear disintegration per second).

3. Radionuclides in ***bold italics*** are those measured in all or part of this study.

4. Radionuclides marked with an asterisk* are the radon isotopes and their short half-life daughters.

5. Dose conversion factors not given by the IAEA are left blank and are taken as negligible.

6. Uranium-238 and uranium-235 occur naturally in the approximate activity ratio 21 : 1.

7. Gross alpha activity, as measured in this study, is taken to be the sum of the activities (in becquerel) of all the alpha emitters (excluding radon and radon daughters), per litre of water.

8. Gross beta activity, as measured in this study, is taken to be the sum of the activities (in becquerel) of all the beta emitters (excluding radon daughters), per litre of water. The list of beta emitters includes potassium-40, a naturally occurring radionuclide which is found in water, but which does not form part of the uranium-238, uranium-235 or thorium-232 decay series. It is not of interest in dose calculations because its concentration in the body is essentially independent of intake.

Table A4.1: Uranium-238 series radionuclides

Radionuclide	Type of radiation emitted	Annual dose per unit activity concentration in water (mSv/a) per (Bq/ℓ)
Uranium-238	Alpha	0,33
Thorium-234	Beta	0,0027
Protactinium-234m	Beta	
Uranium-234	Alpha	0,036
Thorium-230	Alpha	0,15
Radium-226	Alpha	0,27
Radon-222*	Alpha	
Polonium-218*	Alpha	
Lead-214*	Beta	0,00012
Bismuth-214*	Beta	0,000087
Polonium-214*	Alpha	
Lead-210	Beta	0,59
Bismuth-210	Beta	0,0010
Polonium-210	Alpha	1,0

Table A4.2: Uranium-235 series radionuclides

Radionuclide	Type of radiation emitted	Annual dose per unit activity concentration in water (mSv/a) per (Bq/ℓ)
Uranium-235	Alpha	0,034
Thorium-231	Beta	0,00027
Protactinium-231	Alpha	0,52
Actinium-227	Beta	0,85
Thorium-227	Alpha	0,0080
Radium-223	Alpha	0,11
Radon-219*	Alpha	
Polonium-215*	Alpha	
Lead-211*	Beta	0,00015
Bismuth-211*	Alpha	
Thallium-207*	Beta	

Table A4.3: Thorium-232 series radionuclides

Radionuclide	Type of radiation emitted	Annual dose per unit activity concentration in water (mSv/a) per (Bq/ℓ)
Thorium-232	Alpha	0,167
Radium-228	Beta	0,886
Actinium-228	Beta	0,00034
Thorium-228	Alpha	0,064
Radium-224	Alpha	0,069
Radon-220*	Alpha	
Polonium-216*	Alpha	
Lead-212*	Beta	0,0057
Bismuth-212*	Alpha 36% Beta 64%	0,00021
Thallium-208*	Beta	
Polonium-212*	Alpha	

APPENDIX 5

INTER LABORATORY SPLIT SAMPLE QUALITY CONTROL UNDERTAKEN FOR THE MOOI RIVER (WONDERFONTEINSPRUIT) CATCHMENT RADIOACTIVITY MONITORING PROGRAMME.

Appendix 5

INTER LABORATORY SPLIT SAMPLE QUALITY CONTROL UNDERTAKEN FOR THE MOOI RIVER (WONDERFONTEINSPRUIT) CATCHMENT RADIOACTIVITY MONITORING PROGRAMME

1. **Introduction:**

The purpose of the split sample interlaboratory quality control exercise was to test the validity of the radiological analyses of the laboratory designated as no 3, which is being used as the monitoring laboratory for the Mooi River catchment radiological monitoring programme.

Two other laboratories were used for the split sample testing, viz., another local laboratory (designated no 1) and an international laboratory (designated no 2). In addition to the three laboratories who participated in the study, three other local laboratories were invited to participate, but declined.

2. **Procedure:**

From three sample sites in the Mooi River Catchment, two sites were chosen with relatively high radioactivity levels (designated A and B), and one site with low radioactivity levels (designated C). These sites were sampled on the 2 October 1997, a single grab sample being well mixed and then split into three containers for the respective three laboratories. The samples were delivered immediately to both the two local laboratories and to the local agent of the international laboratory, where samples were filtered and acidified prior to dispatch for radiological analysis.

3. **Units of measurement:**

In order not to put unfair pressure on the laboratories, the reporting units of measurement were left up to the reporting laboratories themselves, to avoid any consequent claims of unfamiliarity with the reporting units. Laboratory 1 chose to report nuclide results in μg/ℓ (ppb), while laboratory 3 reported results of the nuclide analyses in mBq/ℓ. Laboratory 2 clearly had a problem with units of measurement, and the distinction between Bq/ℓ and mBq/ℓ, two sets of numerically identical results being reported. In the table of results given in this report all nuclide analysis results are converted where necessary into the common unit of measurement of mBq/ℓ. Gross alpha and beta activities were left in the units in which they were reported of Bq/ℓ.

4. **Discussion of results of the split sample exercise:**

1) Alpha and beta activity: Only two laboratories reported alpha and beta activities, viz. Laboratory 2 and 3. Laboratory 2 reported slightly higher alpha activity than laboratory 3. Beta activities of laboratory 3 were considerably higher than that of laboratory 2. While there is reasonable agreement between the two laboratories for gross alpha activity, there appears to be a problem with the measurement of beta activity.

2) Uranium-238: The results shown by laboratory 1 and 3 are of the same order. The first set of results given by laboratory 2 (i.e. 2a) are three orders of magnitude too low, and are not consistent with the measured alpha activity. The revised results reported by laboratory 2 (i.e. 2b) are in reasonable agreement with laboratory 1 and 3. The U-238 to U-235 activity ratio for the results on sample A were close to the expected ratio of approximately 21:1 for laboratories 2 and 3,

indicating that there is internal consistency between these two variables. The ratio for laboratory 1 was 32:1, indicating that the U-238 value reported was probably on the high side, as the U-235 values agree well between laboratories 1, 2b and 3.

3) Uranium-235: The results reported by laboratory 1 and 3, and the revised results of laboratory 2 (i.e. 2b) are in good agreement. The first set of results reported by laboratory 2 (i.e. 2a) are three orders of magnitude too low.

4) Thorium-232: The results reported by all three laboratories are in good agreement and all reported very low thorium activity concentrations.

5) Radium-224: Radium 224 was only measured by laboratories 2 and 3. Radium-224 is a daughter of the parent nuclide of the thorium-232 chain. As all three laboratories agreed that the thorium-232 values are very low, it can be reasonably assumed that the radium-224 values are also low. Laboratory 3 correctly reported low radium-224 values for all three samples, while laboratory 2 (revised results, 2b) reported a high value for radium-224 in sample C. The radium-224 value here exceeds the measured alpha activity by a factor of ten.

6) Radium-226: Radium-226 is a daughter of the uranium-238 chain, and there is consequently expected to be some relationship between the measured activities. Due to the 3 orders of magnitude uncertainty in the result of laboratory 2 (results 2a and 2b) it is impossible to draw any reliable conclusions where these differ from the laboratory 3 results.

5. **Conclusions:**

1) There appears to be reasonable agreement in the measurement of gross alpha activity, uranium-238, uranium-235 and thorium-232.
2) Agreement is poor for beta activity measurement.
3) For radium-224 and -226 it is not possible to draw firm conclusions as a consequence of the uncertainty in the laboratory 2 results.
4) Laboratory 2 needs to be more careful in reporting units and order of magnitude of the reported nuclide concentrations.
5) Apart from the known problem of the beta activity measurement, the results of the inter laboratory study confirmed the accuracy of the results of laboratory 3, in particular for alpha activity, uranium-238, uranium-235 and thorium-232. As regards the results for radium-224 and -226, these are internally consistent with the results for the three parent nuclides for laboratory 3.
6) The international laboratory (2) chosen as a reference laboratory clearly has problems both with order of magnitude or units of reporting of the results, and with internal consistency of results between the radium nuclides and the parent nuclides and needs to address this problem. The three samples, marked A, B and C, were split samples collected in one container and poured into the three containers for the three laboratories. The laboratories themselves filtered and acidified the samples on receipt.

- Laboratory 1 returned results on 3 November 1997.
- Laboratory 2 first supplied final results on 25 November 1997 (designated Lab 2a). It was pointed out to Lab 2, that the U-238 activity reported of 2,49 mBq/ℓ for sample A was not consistent with the high alpha activity found of 5,19 Bq/ℓ. Lab 2 subsequently reported a “corrected” 2nd set of results (Lab 2b),

and indicated that four nuclides, viz., U-238, U-235, Ra-224 and Ra-226 should have been given as Bq/ℓ and not as mBq/ℓ.

- Laboratory 3 returned results on 12 December 1997.

RESULTS OF SPLIT SAMPLES QUALITY CONTROL STUDY (RADIOACTIVITY): 1997

Sample A:

Variable	Lab 1	Lab 2a	Lab 2b	Lab 3
Alpha activity (Bq/ℓ)	-	5,19	5,19	3,70
Beta activity (Bq/ℓ)	-	1,63	1,63	6,30
Uranium-238	3100 mBq/ℓ (250 ppb*)	2,49 mBq/ℓ	2490 mBq/ℓ	2000 mBq/ℓ
Uranium-235	96 mBq/ℓ (1,2 ppb)	0,113 mBq/ℓ	113 mBq/ℓ	92,8 mBq/ℓ
Thorium-232	<4 mBq/ℓ (<1ppb)	<2,58 mBq/ℓ	<2,58 mBq/ℓ	1,5 mBq/ℓ
Radium-224	-	-0,00354 mBq/ℓ	-3,54 mBq/ℓ	<1,2 mBq/ℓ
Radium-226	-	0,373 mBq/ℓ	373 mBq/ℓ	156 mBq/ℓ

* 1ppb U-238 = 12,4 mBq/ℓ
1ppb U-235 = 79,7 mBq/ℓ
1ppb Th-232 = 4,0 mBq/ℓ

Sample B:

Variable	Lab 1	Lab 2a	Lab 2b	Lab 3
Alpha activity (Bq/ℓ)	-	4,07	4,07	2,90
Beta activity (Bq/ℓ)	-	0,625	0,625	6,80
Uranium-238	1984 mBq/ℓ (160 ppb*)	1,84 mBq/ℓ	1840 mBq/ℓ	1490 mBq/ℓ
Uranium-235	56 mBq/ℓ (0,7 ppb)	0,0832 mBq/ℓ	83,2 mBq/ℓ	70,6 mBq/ℓ
Thorium-232	<4 mBq/ℓ (<1ppb)	<2,58 mBq/ℓ	<2,58 mBq/ℓ	1,5 mBq/ℓ
Radium-224	-	0,0561 mBq/ℓ	56,1 mBq/ℓ	<1,4 mBq/ℓ
Radium-226	-	0,156 mBq/ℓ	156 mBq/ℓ	42,7 mBq/ℓ

* 1ppb U-238 = 12,4 mBq/ℓ

Sample C:

Variable	Lab 1	Lab 2a	Lab 2b	Lab 3
Alpha activity (Bq/ℓ)	-	0,0550 Bq/ℓ	0,0550 Bq/ℓ	<0,66
Beta activity (Bq/ℓ)	-	0,226 Bq/ℓ	0,226 Bq/ℓ	2,70
Uranium-238	30 mBq/ℓ (2,4 ppb*)	0,0571 mBq/ℓ	57,1 mBq/ℓ	31,7 mBq/ℓ
Uranium-235	<8 mBq/ℓ (<0,1 ppb)	0,00259 mBq/ℓ	2,59 mBq/ℓ	1,4 mBq/ℓ
Thorium-232	<4 mBq/ℓ (<1ppb)	<2,58 mBq/ℓ	<2,58 mBq/ℓ	1,5 mBq/ℓ
Radium-224	-	0,648 mBq/ℓ	648 mBq/ℓ	<5,3 mBq/ℓ
Radium-226	-	0,227 mBq/ℓ	227 mBq/ℓ	<4,2 mBq/ℓ

* 1ppb U-238 = 12,4 mBq/ℓ

APPENDIX 6

QUALITY CONTROL AND VALIDATION DONE IN THE ATOMIC ENERGY COMMISSION LABORATORY

A FAANHOF

APPENDIX 7

EVALUATION OF DOSE FROM THE DRINKING WATER PATHWAY AS OPPOSED TO OTHER POSSIBLE PATHWAYS OF EXPOSURE

COUNCIL FOR NUCLEAR SAFETY

Appendix 6

QUALITY CONTROL AND VALIDATION DONE IN THE AEC LABORATORY

The AEC's Radioanalytical Laboratories has fully documented validated procedures compiled in a Quality Management System (QMS). The Quality System designed and implemented by Radioanalysis complies with all the requirements of ISO Guide 25 (SABS 0259). This means, inter alia, that only properly documented and validated analytical methods are used, that these methods are applied by technically trained and competent personnel, that systems are available and used to maintain the performance of facilities and methods, and that a programme of continuous quality improvement is actively pursued. Audits and surveillance programmes by clients are encouraged within the constraints of security, safety and proprietary rights of the other clients. The QMS is regularly updated with new and revised analytical procedures. Of the analytical procedures have been approved upon by the Council for Nuclear Safety (CNS). The Quality System is audited annually by Corporate Quality Services of the AEC for compliance with ISO Guide 25. Some of the larger clients also prefer to perform their own independent audits. Application for accreditation by the National Laboratory Accreditation Service (NLA) is pending and expected during 1998.

The following independent audits have been carried out on the quality systems. Uncontrolled copies of these audit reports are available on request.

- RA-AUD-002 (02): Audit by the Council for Nuclear Safety on methods for analysis of U and Ra in water (November 1996) (1997-01-13).
- RA-AUD-005 (02): Audit of Radioanalysis Quality System by AEC Corporate Quality Services on 1997-08-19 (1997-10-27)
- RA-AUD-006 (02):Audit (1997) by the USA Food and Drug Administration on the purity certification of fission molybdenum by Radioanalysis (1997-11-10).
- RA-AUD-007 (02): Inspection by the Council for Nuclear Safety on the implementation of gamma spectrometry procedures (97-10-29) (1997-11-14).
- RA-AUD-008 (02): Inspection by the Council for Nuclear Safety on the implementation of procedures for gross α/β -counting for EET (98-12-12) (1998-03-02).

The RA laboratories participate in national and international inter laboratory performance studies. The results are fully documented in the QMS. The RA laboratories are part of the IAEA's world wide network of recognised radioanalytical laboratories (ALMERA) and of the International Comprehensive Nuclear-Test Ban Treaty Organisation (CTBTO). Information on the most recent interlaboratory performance studies that demonstrate the ability of the laboratory to provide an acceptable analytical service, are contained in the following documents. Uncontrolled copies of these are available on request:

- RA-PFT-001 (01): Council for Nuclear Safety intercomparison study on the determination of uranium and radium in aqueous samples (1996-08-01).
- RA-PFT-002 (01): PROCORAD intercomparison study on the determination of radionuclides in urine samples (1997-01-13).
- RA-PFT-005 (01): IAEA: ALMERA intercomparison study on the determination of radionuclides in environmental samples SOIL-1 (soil) and SED-1 (sediment) (1998-05-11).
- RA-PFT-007 (01): International study of essential and toxic elements in bread flours: P-RBF and P-WBF (1997-04-07).
- RA-PFT-008 (01): International study on major and trace elements in IAEA-331 (spinach) and -336 (lichen) (1997-04-21).
- RA-PFT-010 (01): Council for Nuclear Safety intercomparison exercise on the determination of radium and uranium in environmental water (1998-05-11).
- RA-PFT-012 (01): Intercomparison by the Department of Water Affairs and Forestry on the measurement of naturally occurring radionuclides (1998-02-23).

To supply full documentation of the QMS and the analytical procedures is not practical due to the vast amount of paper involved. However, the QMS can be reviewed and/or audited by the Department of Water Affairs and Forestry (DWAF) whenever required. The main topics dealt with are:
The quality policy statement inferring the mission and commitment of all personnel to comply with the policies and procedures laid down.

The normative references based on SABS 0259 (ISO/IEC 25 equivalent), and internal documents describing:

- the management system to generate, implement and control documents,
- the management system for the validation of the analytical methods used by the laboratories,
- the management system for training and qualification of analytical personnel,
- the management system for registration, handling and closing of non-conformance affecting quality,
- the management system to regulate the production of quality products and services by the laboratories,
- the list of controlled documents and forms issued by the laboratories,
- the definition of terms and abbreviations used by the laboratories, and
- the list of designated personnel with particular responsibility and authority.

The quality system describing:

- the strategy for achieving quality at the laboratories, and the objective of the system,
- the organisation, responsibilities and authority to manage the system,
- the controlled quality assurance documents and records of technical information,
- the quality audit, review and surveillance of the system,
- the secure storage of operational records, the confidentiality of proprietary information of the client and the access regulations to the laboratories,
- the selection, appointment, training and qualification of personnel.

-

The operational system describing:

- the client's liaison, promotion, advertising, and marketing administration,
- the client interface to manage, set services, non-routine services, ad hoc services and projects,
- facilities used in the laboratories, the monitoring of their performance, their calibration and the control and use of standards and certified reference materials,
- the execution of analysis like sampling, sample receipt, processing using validated and non-established methods,
- the reporting of results and record keeping,
- the capabilities of the analytical methods through validation and inter-laboratory comparisons,
- the type of nonconformance like incidents, deviations and complaints, and the handling of this nonconformance, and
- other aspects affecting quality like the resources of materials used in the laboratories, and the use of subcontractors.

Instruments are calibrated regularly with internationally traceable reference standards according to the procedures laid down in the QMS. In-house reference samples are analysed at regular intervals to evaluate the performance of the analytical procedures. Storage of data and samples is prescribed by the QMS. All raw data are stored for 3 years or more. The work is performed by and under supervision of competent staff registered as professional natural scientists with the SA Council for Natural Scientific Professions. The radioanalytical laboratory currently employs 31 staff members. The qualifications of the key personnel are available on request.

Appendix 7

EVALUATION OF DOSE FROM THE DRINKING WATER PATHWAY AS OPPOSED TO OTHER POSSIBLE PATHWAYS OF EXPOSURE

Introduction

The transport of radionuclides through terrestrial and aquatic biota can result in the contamination of the human diet. Ingestion of radionuclides in foods can be an important contributor to the total dose received by an individual or critical (population) group.

The models presented here are intended to be simple screening models for the purpose of estimating the potential impacts, of specific water use scenarios, to hypothetical critical groups in the absence of any site-specific data.

The radionuclides of concern are the long-lived radionuclides of the ^{238}U and ^{232}Th decay chains.

Since simple transfer factors based upon concentration factors are used, steady state conditions are assumed with regard to the long term build-up of contaminants in the various environmental compartments i.e. it is assumed for example that the use of contaminated water has been a long term process.

The models are not intended for use in modeling infrequent events e.g. a discrete batch discharge. They are intended for situations in which the long term average radionuclide concentrations in water are reasonably well known; i.e. they are not intended to predict doses from single grab sample results.

The result merely indicates the range of potential hazard that may arise if the water is put to a particular use. This value is compared to a defined criteria (e.g. indicated dose >250 $\mu Sv.y^{-1}$) to assist in a decision making process to determine whether further investigations are required e.g. initiate further sampling programme; identify source: identify actual critical groups: implement control over source and/or initiate remedial action.

In reality an exposed group of individuals will receive widely varying doses from an exposure pathway, these models are intended to indicate the potential range of dose to a critical group or person for each exposure pathway.

Since the consumption factors and transfer factors are required to cover all possible situations and types of critical groups and taking into account the lack of data on transfer factors in semi-arid environments the maximum values used are conservative (in order to ensure that potential doses are not underestimated); and merely indicate the maximum likely dose within a poorly quantified scenario.

Where significant doses are indicated by the model, the implication is that the actual situation on the ground should be investigated further to define mitigating factors and the actual water uses.

Scaling

If site specific data is available the results obtained using the default values can be scaled to give a more realistic estimate of dose. For example if the water consumption of an identified group of adults is known to be only 250 litres from the contaminated source the resulting dose can be scaled i.e.

$\mu Sv/(a.Bq.l^{-1}) \times (250/730)$

Scaling can be applied to any consumption rate, occupation factor, irrigation rates, transfer parameter etc where site specific information is available.

Interpretation

It is proposed that where a value exceeds 250 μSv/a that consideration be given to site specific investigations to better quantify the dose e.g. determine actual critical groups, their water use and food consumption rates.

Ingestion Dose Coefficients

These have been taken from ICRP-72 and indicate the committed effective dose per unit intake in $\mu Sv.Bq^{-1}$.

The Dose Coefficients used in the model are given below for a child (age range 1-2 years) and for adult members of the public.

Table 1: Ingestion Dose Coefficients

	DC_{child}	DC_{Adult}
^{238}U	0,12	0,05
^{234}U	0,13	0,05
^{230}Th	0,41	0,21
^{226}Ra	0,96	0,28
^{210}Pb	3,6	0,69
^{210}Po	8,8	1,2
^{232}Th	0,45	0,23
^{228}Th	0,37	0,07
^{228}Ra	5,7	0,69
^{224}Ra	0,66	0,07
^{235}U	0,13	0,05
^{231}Pa	1,3	0,71
^{227}Ac	3,1	1,1
^{227}Th	0,07	0,009
^{223}Ra	1,1	0,1

Transfer Factors

In the absence of data specific to arid South African conditions default values have been based mostly upon a literature survey of data applicable to temperate European and North American situations. The values selected are conservative and represent in most cases the upper bound of reported values (95% CL).

The more important references reviewed to obtain parameter and consumption values are given in the reference section at the end of this document.

Ranges of Parameter values are given in a number of cases to indicate the range of recorded variability and the degree of conservatism: these values are taken from various IAEA summaries. It should be noted that these ranges reflect variations associated with different parts of the world as well as between different crop species or types of farm animals. The values used in the simple model are not species specific but refer to very broad generic categories of edible pasture, vegetables, fruits, etc (e.g. leafy vegetables applies to all types of leafy vegetables and pasture includes grass, wild forage, browse, hay etc).

Uptake of Radionuclides from Soil by Edible Portions of Vegetation

The soil to plant concentration factor, F_v, can be applied to animal feeds (e.g. pasture, forage, browse and plant based feed) and is referred to as F_{v1}. In addition F_{v2} values are defined for fresh food crops consumed by humans.

The concentration factor reflects only the uptake of radionuclides from the soil via roots and excludes the effects of deposition of nuclides onto plant surfaces by resuspension, deposition and fallout.

F_{v1} = (Bq.g^{-1} Dry weight plant) / (Bq.g^{-1} dry weight soil)

F_{v2} = (Bq.g^{-1} Fresh weight plant) / (Bq.g^{-1} dry weight soil)

Default Annual Consumption Factors for Exposed Individuals in Critical Groups

Dietary composition varies widely around the world and can vary widely within the same country e.g. South Africa. The great majority of default values reported in the literature and used in modeling are based upon European or North American diets with very limited data available on African diets and consumption rates.

The following should be noted:

1) Due to the difficulty in establishing an "average" South African diet given the first-world/third-world mixture of potential critical groups; two default diets have been derived (refer to IAEA 57 and IAEA 57 redraft) based upon per caput consumption values considered to be representative of different geographical regions. Diet 1 corresponds to African per caput values and Diet 2 to a European diet: the major difference in these diets being in the milk, meat and vegetable consumption factors. (Note: default water and fish consumption is assumed to be the same).

2) These consumption values are for use in screening assessments and should ensure that all types of potential critical groups are covered e.g. rural dwellers, subsistence farmers, modern farmers and other groups with a variable dietary intake.

3) Values for infants have been derived by scaling from default adult consumption rates based upon values from the literature (e.g. ICRP-29).

4) The values were derived after review of a wide range of literature (e.g. IAEA 1982, 1986, 1994, 1996, ICRP 1978). It should be noted that they are not the highest per capita consumption values reported in the literature. Extensive use was made of interpolation and rounding in deriving these values.

Table 2: Annual Food Consumption Parameters for Diet 1

CATEGORY (Kg per year fresh weight)	ADULT	Child (1-2 years)
Water	730	260
Freshwater Fish	25**	1
Milk (Litres)	80	180
Meat	35	10
Cereals and grains	120	50
Leafy Vegetables	55	22,5
Root crops	170	70
Fruit, nuts, pulses	40	15

Table 3: Annual Food Consumption Parameters for Diet 2

CATEGORY (Kg per year fresh weight)	ADULT	CHILD (1-2 years)
Water	730	260
Freshwater Fish	25**	1
Milk (Litres)	250	300
Meat	100	20
Cereals and grains	150	60
Leafy Vegetables	55	22,5
Root crops	170	70
Fruit, nuts, pulses	75	30

****** (Applicable to both recreational and subsistence fishermen: there is uncertainty as to whether this value adequately represents the intake of certain subsistence groups utilising this resource in the Gauteng area)

Note: For comparison to the above diets maximal per capita (i.e. average) annual consumption rates are given below from around the world.

These values are average values for large geographical regions: therefore higher adult maxima can occur in specific countries or specific groups within such countries (e.g. meat: Finland and Laplanders).

Milk:	**Oceania:**	**410 liters**
Meat:	**North America:**	**205 kg**
Fresh water fish:	**Far East:**	**35 kg**
Vegetables, roots, grain, nuts etc:		**600 kg**

Default water consumption rates are highly variable around the world ranging from around 350-850 liters per annum.

Table 4: Animal Daily Food and Water Consumption Default Values

Animal	Water ($L\ d^{-1}$)	Dry Feed[a] ($Kg\ d^{-1}$)
Milk or Beef Cow	75	25

a. Feed, pasture, browse or forage

The above default values cover all breeds and intensities of dairy farming or beef production. Since dairy cows have higher intake demands the defaults are based on dairy cows. Ranges reported in the literature for all breeds and climates and milk production rates are as follows:

Water = 20 - 110 Litres per day.
Dry feed = 5 - 25 kg per day.

Models Involving Irrigation

Models involving irrigation were calculated in a three-stage approach:

1. Calculating the concentration (C_{iv}) in pasture and feed and crops

2. Calculating the concentration in milk, meat

3. Calculating the effective dose

An example of the approach used is given in Appendix 7A.

The various parameter values used to calculate C_{iv} in pasture, forage, feed and crops are given in the text.

MODEL CALCULATIONS

Introduction

A brief overview is given of the structure of the models used in the database. Relevant diet values from Diet 2 are provided as example values since these are the highest of the two diet groups.

1. Drinking Water

Assumptions:

- Activity Concentration: 1 $Bq.L^{-1}$ per radionuclide
- No dilution: No removal: No treatment prior to consumption
- Water consumption:
  Adult = 730 $L.y^{-1}$
  One year old = 260 $L.y^{-1}$

Drinking Water Equation

$\mu Sv\ y^{-1} = 1\ (Bq.L^{-1})$ X $730\ (L.y^{-1})$ X DC_{Adult} $(\mu Sv.Bq^{-1})$

$\mu Sv.y^{-1} = 1\ (Bq.L^{-1})$ X $260\ (L.y^{-1})$ X DC_{Child} $(\mu Sv.Bq^{-1})$

CED = water concentration x consumption x dose coefficient

(CED = Committed Effective Dose)

2. Consumption of Fish Living in Contaminated Water

Assumptions:

- Activity Concentration: 1 $Bq.L^{-1}$ of relevant radionuclide
- No dilution: no removal: no treatment.
- Assumes a long-term stable contamination situation.
- Fish Consumption (edible wet weight)
  Adult = 25 $kg.y^{-1}$
  One year old = 1 $kg.y^{-1}$

Fish Consumption Equation

$\mu Sv.y^{-1} = 1\ (Bq.L^{-1})$ X Bp $(Bq.L^{-1} / Bq.Kg^{-1})$ X $25\ (Kg.y^{-1})$ X DC_{Adult} $(\mu Sv.Bq^{-1})$

$\mu Sv.y^{-1} = 1\ (Bq.L^{-1})$ X Bp $(Bq.L^{-1} / Bq.kg^{-1})$ X $1\ (kg.y^{-1})$ X DC_{Child} $(\mu SV.Bq^{-1})$

CED = concentration x bioaccumulation factor x annual consumption x dose coefficient.

Bioaccumulation Factors for Freshwater Fish

Under equilibrium conditions, the incorporation of radioactivity into fish can be expressed as the bioaccumulation factor B_p defined as:

"The ratio of the activity concentration in fish tissue to that in water which is normally expressed as $Bq.kg^{-1}$ wet weight fish per $Bq.kg^{-1}$ (or L^{-1}) water (units of $L.kg^{-1}$)". The activity concentration in fish tissue usually refers to the edible portion of the fish wet mass.

The values can be used to predict activity levels in edible fish tissue from activity levels in water under steady state conditions.

Table 5: Bioaccumulation factor ($B_{p)}$ values: Uptake from Water into Fish Tissue.

Element	Environment	Biota	Concentration Factors	Range
			B_p (Units: $L.kg^{-1}$)	
U	Fresh water	Fish	5.00E+01	0,3-50
Ra	Fresh water	Fish	2.00E+02	0,3-200
Po	Fresh water	Fish	5.00E+02	10-500
Pb	Fresh water	Fish	2.00E+03	100-2000
Th	Fresh Water	Fish	1.00E+03**	30-10000*
Ac	Fresh Water	Fish	3.30E+02	15-330
Pa	Fresh Water	Fish	3.00E+01	10-30

*Higher values have been reported recently up to 60000 in a French study.
** A lower default value (1000) was used in the model based on South African data.

Bio-accumulation parameter values vary widely according to many factors e.g. fish type, type of water body, feeding patterns and feeding habits (e.g. carnivorous, omnivorous, herbivorous), trophic level, water chemistry, stable element concentrations, pH, nutrient levels, eutrophic level of water body, water temperature, size of fish, age, migratory behaviour, physico-chemical form of the radionuclide, dissolved mineral content, sedimentation and resuspension processes as well as with different radionuclides, in addition reported values in the literature for specific radionuclides in different freshwater environments can vary by several orders of magnitude. In addition to the above factors inadequate sampling and radiochemical analysis programs can contribute to uncertainties.

It should also be noted that the transfer factors express the summed fractional uptake into the fish via many pathways e.g. direct uptake from water through the gills, skin and gut: uptake from sediment; uptake through various trophic feeding levels and routes.

The range of this potential variation for fish is indicated in the above Table.

The availability of site specific data is of great importance to provide realistic estimates of effective dose through the consumption of fish.

3. Consumption of Milk from Cows Grazing on Feed Irrigated with Contaminated Water

Assumptions

- Concentration: 1 $Bq.L^{-1}$ of relevant radionuclide.
- No dilution: no removal: no treatment of water prior to irrigation.
- The sole source of all milk is obtained from the cow i.e. no dilution with uncontaminated milk.
- Cows always graze on contaminated land e.g. pasture, lucerne etc.

- Assumes an irrigation rate of 750 $L.y^{-1}$ per m^{-2} (source: mean value for irrigation farmers in Lower Vet river). The model assumes only 1 year of irrigation with contaminated water prior to the cows commencing grazing.

- Steady state conditions: i.e. minimal leaching of activity from soil.

- Excludes uptake through spray irrigation through deposition on leaves.

- Covers all types of irrigation.

- Excludes uptake arising from eating soil.

- Accounts for decay.

- Milk Consumption (litres)
  Adult = 250 $L.y^{-1}$
  One year old = 300 $L.y^{-1}$

- Feed consumption = 25 000 $g.d^{-1}$ (dry)

MILK CONSUMPTION EQUATION

$\mu Sv.y^{-1} = C_{iv}$ X 25000 (Dry $g.d^{-1}$) X F_M X 250 (L) X DC_{Adult} ($\mu Sv.Bq^{-1}$)

$\mu Sv.y^{-1} = C_{iv}$ X 25000 (Dry $g.d^{-1}$) X F_m X 300 (L) X DC_{Child} ($\mu Sv.Bq^{-1}$)

CED = concentration in feed ($Bq.g^{-1}$) x dry feed consumption: grams per day x f_m (feed to milk transfer factor: per $Bq.L^{-1}$ milk per Bq.day intake) x annual milk consumption (L) x dose coefficient.

Note: Refers to one year of irrigation: assumes a 15 cm plough depth containing 240 kg of dry soil per m^2.

Table 6: Default Soil to Plant Transfer Factors: F_{v1} for all Types of Pasture, Grass, Browse and Forage Vegetation.

Element	Concentration Factors	
	F_{V1}	
	Minimum	Maximum
U	1.00E-05	2.00E-01
Pa	1.00E-02	1.00E-01
Ac	4.00E-03	1.00E-01
Ra	1.00E-03	4.00E-01
Po	5.00E-04	1.00E-01
Pb	2.00E-04	5.00E-01
Th	5.00E-05	1.00E-01

Unit: ($Bq.g^{-1}$ dry plant per $Bq.g^{-1}$ dry soil)

Feed to Milk transfer Factors: (Fraction of daily intake taken into milk):
Transfer Coefficients F_m for Cow's Milk

The transfer of radionuclides from an animal's feed to milk is commonly described by using the transfer coefficient F_m defined as:

"The fraction of the animals total daily intake of a radionuclide that is transferred to each litre of milk per day".

Note: The values given below may be applied to cow, goat or sheep milk.

Table 7: Feed to Milk transfer Factors: (Fraction of daily intake taken into milk): Transfer Coefficients F_m

Element	Transfer Coefficient	
	F_m	
	units.d.L^{-1}	
	Minimum	Maximum
U	7.30E-05	6.10E-04
Pa	2.50E-06	5.00E-06
Ac	2.00E-05	2.00E-04
Ra	7.00E-06	1.3E-03
Po	1.00E-04	3.00E-03
Pb	3.00E-05	3.00E-04
Th	2.50E-06	5.00E-06

4. Consumption of Milk from Cows Drinking Contaminated Water

Assumptions

- Concentration = 1 Bq.L^{-1} of relevant radionuclide.
- The sole source of all milk is obtained from the cow i.e. no dilution with uncontaminated milk.
- Cows only drink contaminated water.
- Steady state conditions apply.
- Concentration = 1 Bq.L^{-1} of relevant radionuclide.
- No dilution: no removal: no treatment of water prior to drinking.
- Milk is obtained direct from the animal i.e. no dilution with uncontaminated milk.
- Cow Water Consumption = 75 L.d^{-1}
- Milk Consumption (litres)
  Adult = 250 L.y^{-1}
  One year old = 300 L.y^{-1}

Milk Consumption Equation

$\mu Sv.y^{-1} = 1\ (Bq.L^{-1}) \times 75\ (L.d^{-1}) \times F_m \times 250\ (L) \times DC_{Adult}\ (\mu Sv.Bq^{-1})$

$\mu Sv.y^{-1} = 1\ (Bq.L^{-1}) \times 75\ (L.d^{-1}) \times F_m \times 300\ (L) \times DC_{Child}\ (\mu Sv.Bq^{-1})$

CED = concentration in water x w_c (daily water consumption) x F_m (water to milk transfer factor: Bq.day intake per Bq.L^{-1}) x annual milk consumption (L) x dose coefficient.

For F_m values refer to Table 7.

5. Consumption of Meat from Cattle Grazing on Feed Irrigated with Contaminated Water

Assumptions

- Concentration = 1 $Bq.L^{-1}$ of relevant radionuclide.
- No dilution: no removal: no treatment of water prior to irrigation.
- The sole source of all meat consumed is obtained from the cattle.
- Cattle always graze on contaminated land e.g. pasture, lucerne etc.
- Assumes an irrigation rate of 750 $L.y^{-1}$ year per m^{-2} (source: mean value for irrigation farmers in Lower Vet River). The model assumes only 1 year of irrigation with contaminated water prior to the cows commencing grazing.
- Steady state conditions: i.e. no leaching of activity from soil.
- Excludes uptake through spray irrigation through deposition on leaves.
- Covers all types of irrigation.
- Excludes uptake arising from eating soil.
- **Meat Consumption (kg)**
  Adult = 100 $kg.y^{-1}$
  One year old = 20 $kg.y^{-1}$
- **Feed consumption**
  25 $kg.d^{-1}$

Meat Consumption Equation

$\mu Sv.y^{-1} = C_{iv}$ X 25000 (Dry $g.d^{-1}$) X F_F X 100 (kg) X DC_{Adult} ($\mu Sv.Bq^{-1}$)

$\mu Sv.y^{-1} = C_{iv}$ X 25000 (Dry $g.d^{-1}$) X F_F X 20 (kg) X DC_{Child} ($\mu Sv.Bq^{-1}$)

CED = concentration in feed ($Bq.g^{-1}$) x dry feed consumption g per day x F_F (feed to meat transfer factor: per $Bq.kg^{-1}$ meat per Bq.day intake) x annual meat consumption (kg) x dose coefficient.

Transfer Coefficients F_f for Animal Flesh

Beef and Cows

The transfer of radionuclides from an animal's feed (pasture, grass, forage) to edible animal products is commonly described by using the transfer coefficient F_f defined as:

"The fraction of the animals total daily intake of a radionuclide that is transferred to each kg of flesh at equilibrium or at time of slaughter".

The values below are derived for beef meat but may be may be applied to all types of edible beef and cow products as well as pigs, goats, horses and game animals.

Table 8: Transfer Coefficients F_f

Element	Transfer Coefficient	
	F_F	
	(Units: $d.kg^{-1}$)	
	Minimum	Maximum
U	1.60E-06	3.00E-02
Pa	1.60E-06	5.00E-03
Ac	2.00E-05	4.00E-04
Ra	1.00E-04	5.00E-03
Pb	1.00E-04	9.10E-04
Po	6.00E-04	5.00E-03
Th	1.60E-06	5.00E-03

6. Consumption of Meat from Animals Drinking Contaminated Water

Assumptions

- Concentration = 1 $Bq.L^{-1}$ of relevant radionuclide.
- The sole source of all meat is obtained from the cattle.
- Cattle only drink contaminated water.
- Steady state conditions apply.
- No dilution: no removal: no treatment of water prior to drinking.
- Water Consumption = 75 $L.d^{-1}$
- **Meat Consumption (kg)**
  Adult = 100 $kg.y^{-1}$
  One year old = 20 $kg.y^{-1}$

Meat Consumption Equation

$\mu Sv.y^{-1}$ = 1 ($Bq.L^{-1}$) X 75 ($L.d^{-1}$) X F_F X 100 (kg) X DC_{Adult} ($\mu Sv.Bq^{-1}$)

$\mu Sv.y^{-1}$ = 1 ($Bq.L^{-1}$) X 75 ($L.d^{-1}$) X F_F X 20 (kg) X DC_{Child} ($\mu Sv.Bq^{-1}$)

CED = water concentration x w_c (daily water consumption) x F_F (water to meat transfer factor: Bq.day intake per $Bq.kg^{-1}$) x annual meat consumption (kg) x dose coefficient.

7. Consumption of Crops Irrigated by Contaminated Water.

Assumptions

- Concentration = 1 $Bq.L^{-1}$ of relevant radionuclide.
- No dilution: no removal: no treatment of water prior to irrigation.
- The sole source of all food consumed is irrigated with contaminated water.
- Assumes an irrigation rate of 750 $L.y^{-1}$ year per m^{-2} (source: mean value for irrigation farmers in Lower Vet River). The model assumes only 1 year of irrigation with contaminated water)

- Steady state conditions: i.e. no leaching of activity from soil.
- Excludes uptake through spray irrigation through deposition on leaves.
- Covers all types of irrigation.
- **Annual Plant Consumption by Humans (f_c)**

  Cereals and Grains:

  Adult = 150 kg
  1 year old = 60 kg

  Root Crops

  Adults = 170 kg
  1 year old = 70 kg

  Leafy Vegetables

  Adults = 55 kg
  1 year old = 22,5 kg

  Fruits and other vegetables

  Adults = 75 kg
  1 year old = 30 kg

  Root crops, leafy vegetables and fruits, nuts etc refers to fresh weight consumption.

Generic Equation

The generic equation applies to the consumption of grains or leafy vegetables or root vegetables or fruits. Insert the appropriate f_{v2} value for the crop to determine the concentration (C_{iv})(Bq.g^{-1}) in the crop (refer to attachment A) and the age specific annual consumption values f_{ca} (adult) and f_{cc} (child).

$\mu Sv.y^{-1} = C_{iv} \times f_{ca}$ (g.y^{-1}) X DC_{Adult} ($\mu Sv.Bq^{-1}$)

$\mu Sv.y^{-1} = C_{iv} \times f_{cc}$ (Dry g.y^{-1}) X DC_{Child} ($\mu Sv.Bq^{-1}$)

CED = concentration in food x annual food consumption (g.y^{-1}) x dose coefficient.

Table 9: Default Concentration factors F_{v2} for all Types of Grains and Cereals e.g. Maize, Wheat, Barley, Sunflower Seeds etc.

Element	Concentration Factor	
	F_{v2}	
	MINIMUM	MAXIMUM
U	2.00E-04	1.30E-03
Pa	2.00E-02	2.00E-02
Ac	3.00E-04	3.00E-04
Ra	2.40E-04	1.00E-02
Pb	4.70E-04	5.00E-02
Po	1.00E-03	2.00E-03
Th	3.40E-06	1.00E-03

Unit: (Bq.g^{-1} dry plant and soil)

Table 10: Concentration Factors F_{v2} For Leafy Vegetables, Root Vegetables And Fruits, Nuts And Pulses.

Element	Concentration Factor F_{v2}					
	Leafy Vegetables		Root Vegetables		Fruits	
	Minimum	Maximum	Minimum	Maximum	minimum	maximum
U	1.20E-04	1.00E-02	2.00E-04	3.00E-02	4.00E-04	4.00E-04
Pa	8.00E-03	8.00E-03	1.00E-02	1.00E-0	5.00E-03	5.00E-03
Ac	1.50E-03	1.50E-03	2.00E-03	2.00E-03	3.00E-04	3.00E-04
Ra	1.00E-04	4.00E-02	4.00E-05	4.00E-02	4.30E-04	4.00E-02
Pb	8.50E-05	3.00E-02	3.00E-05	2.00E-02	1.00E-02 .	1.00E-02
Po	3.00E-04	2.00E-03	2.00E-04	2.00E-03	1.00E-03	1.00E-03
Th	5.00E-06	1.00E-02	1.00E-06	8.00E-04	4.00E-04	4.00E-04

(Unit: $Bq.g^{-1}$ wet plant per $Bq.g^{-1}$ dry soil)

Default % dry weights were used in calculating the above wet weight parameter values: green vegetables (15%): roots (20%) and fruits(10%).

8. External Exposure Arising from Radionuclides in Water

Assumptions

- Concentration = 1 $Bq.L^{-1}$ of relevant radionuclide (radium) in river or lake.
- Steady state conditions.
- The model covers the following exposure scenarios and assumes a total occupancy factor of 300 hours per annum: Swimming, fishing, boating, ski boating, sailboard.

The exposure model is based upon the external gamma dose arising from exposure to radionuclides in the water. It does not estimate any dose that may arise from contaminated sediment, which would require a separate measurement.

Since the primary gamma emitter of the decay chain is radium the concentration of radium should be used in the equation. If radium concentration is not available use the 238U concentration.

The conversion factor calculated below was derived from a simple conservative model given in IAEA 57 page 5+4-56 (1982).

The following assumptions were used:

- 1 $Bq.L^{-1}$ radium
- Mean gamma energy per decay: 1 MeV
- Occupation factor 300 hours per annum.
- Geometry modification factor : 2
- Conversion factor = 0,2 $\mu Sv.y^{-1}$ per $Bq.L^{-1}$ Radium (OF= 300 hours).

Note:

(a) The above dose is minimal compared to other exposure pathways.

(b) The above model can be used for sediments where more significant doses are likely to arise from external exposure to contaminated sediments: in this case the activity per kg (dry) of the sediment would require to be measured for input into the above model.

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Vol 1-3. 1988.

APPENDIX 7A

Calculations Involving Irrigation

Dose from Ingestion of Milk from Cows Grazing on Land which has been Irrigated with Contaminated Water

Adopt NUREG 1.109 approach.

Problem is addressed in three stages.

Stage 1: Concentration of radioactive material in vegetation (C_{iv})

The expression used to derive C_{iv} is eq. A-8 on p. 1.109 - 15. Two components contribute to the total activity concentration.

Component 1 given in the first term of the bracketed expression refers to direct foliar deposition. This term is neglected as this is specifically excluded from the brief.

Component 2 refers to the uptake of radioactivity into vegetation from soil and can reflect long term deposition due to operation of a facility.

The modified expression taken from eq. A-8 for use in the project will therefore be:

$$C_{iv} = C_{iw} \cdot I \cdot \left[\frac{f_i \cdot B_{iv} \cdot \left(1 - \exp(-l_i \cdot t_b)\right)}{r \cdot l_i} \right] \cdot \exp(-l_i \cdot t_h)$$

where

C_{iw} - $Bq \cdot l^{-1}$ of nuclide *i* in water used for irrigation
I - $L \cdot m^{-2} \cdot h$ average irrigation rate during growing season
f_i - fraction of year which crops are irrigated
B_{iv} - soil to vegetable radionuclide concentration factor
ρ - effective surface density of soil $kg \cdot m^{-2}$
λ_i - radiological decay constant
t_b - period of time for which soil is exposed to contaminated water
t_h - hold-up time between harvest and consumption

In the current case, t_b will be assumed to be one year and t_h will be zero, and so $exp(-\lambda_i \cdot t_h)$ will therefore tend to one.

Stage 2: Concentration of radionuclides in milk

The radionuclide concentration in an animal product such as meat or milk is dependent on the amount of contaminated feed or forage eaten by the animal and its intake of contaminated water.

In the current case, the intake of contaminated water is neglected.

The radionuclide concentration C_{im} in milk is given by eq. A-11 of NUREG 1.109 on p. 1.109 - 16.

$$C_{im} = F_{im} \times C_{iv} \times Q_v$$

where

F_{im} - stable element transfer coefficient relating daily intake rate by an animal to concentration in milk, day·L^{-1}.

Q_v - Consumption rate of contaminated vegetable matter, kg·day^{-1}.

Stage 3: Dose to man from ingestion of contaminated milk

The dose D_i, is simply the product of the radionuclide concentration in milk C_{im}, the annual intake of milk Q_m, and the ingestion dose coefficient for the particular nuclide:

$$D_i = C_{im} \times Q_m \times DCF_i$$

thus

$$D_i = C_{iw} \cdot I \cdot \left[\frac{f_i \cdot B_{iv}\left(1 - \exp(-\lambda_i \cdot t_b)\right)}{\rho \cdot \lambda_i} \right] \cdot F_{im} \cdot Q_v \cdot Q_m \cdot DCF_i$$

Note: the above equations can be adapted to provide concentrations of radionuclides in various crop types using the appropriate transfer values. Dose to the consumer may then be calculated in a manner similar to the above example but using the appropriate consumption factors for the various crop types.

APPENDIX 7B:

Significance of dose due to drinking water pathway relative to that of other ingestion pathways

The following table summarises the doses per age group due to the various ingestion pathways. In order to provide the relative significance the percentages are calculated relative to the dose due to the drinking water pathway. In arriving at the relative percentage doses the activity of all nuclides of interest was assumed to be 1 Bq/L.

PATHWAY	% Dose per Pathway Relative to Dose due to Drinking Water Pathway				
	1-2	2-7	7-12	12-17	Adult
Drinking Water	100.00	100.00	100.00	100.00	100.00
Fish	36.81	154.61	259.84	144.52	287.12
Ingestion of Milk	15.61	12.25	10.35	6.21	3.21
Ingestion of Meat	3.10	6.51	9.09	7.89	4.86
Ingestion of Poultry	0.01	0.01	0.02	0.02	0.01
Ingestion of Eggs	0.01	0.03	0.04	0.03	0.04
Ingestion of Root Crops	1.03	1.15	1.52	1.62	0.81
Ingestion of Cereals and Grains	0.69	0.79	0.90	0.80	0.64
Ingestion of Leafy Vegetables	0.36	0.41	0.53	0.55	0.29

APPENDIX 8

CALCULATION OF RADIATION DOSE

METHOD 1

J CARTER

APPENDIX 9

Appendix 8

CALCULATION OF RADIATION DOSE

METHOD 1

This Appendix details the processes and assumptions used to calculate the lifetime average annual radiation dose resulting from the drinking water pathway.

The lifetime average annual dose associated with a sampling site was calculated from the expression:

$$D = \sum_i A_i F_i$$

where: D is the lifetime average annual dose (mSv/a)

A_i is the annual average activity concentration of radionuclide i (Bq/ℓ)

F_i is a proportionality constant for radionuclide i with units of (mSv/a) per (Bq/ℓ).

The determination of the parameters A_i and F_i is described in Sections A8.1 and A8.2 below.

A8.1 Determination of Activity Concentration, A_i

The determination of annual average radionuclide activity concentrations at the various sites was complicated by the following factors:

- not all the radionuclide activity concentrations were measured;
- of those that were measured, not all were measured at all sampling sites;
- fewer radionuclides were measured in the first phase of the study than in the second phase; and
- some new sampling sites were added and some removed during the course of the study.

Details of the sampling data set are given in Table A8.1. The methods of dealing with the complications mentioned above are described in sections A8.1.1 to A8.1.3 below.

Table A8.1 Details of individual radionuclide measurements

1: measured only in phase 1
2: measured only in phase 2
1+2: measured in phases 1 and 2
Shaded areas indicate months during which measurements were made.

Site	Phase 1						Phase 2						Radionuclide												
	J	F	M	A	M	J	J	A	S	O	N	D	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{235}U	^{231}Pa	^{227}Ac	^{227}Th	^{223}Ra	^{232}Th	^{228}Ra	^{224}Ra
1													1			1			1				1	1		1
2													1			1			1				1	1		1
3													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
4													1			1			1				1	1		1
5													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
6													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
6a													1			1			1				1	1		1
7													1+2	2	2	1+2	2	2	1+2	2	2	2	1+2	1+2	2	1+2
7a													1+2	2	2	1+2	2	2	1+2	2	2	2	1+2	1+2	2	1+2
8													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
9													1+2	2	2	1+2	2	2	1+2	2	2	2	1+2	1+2	2	1+2
10													1			1			1				1	1		1
11													1			1			1				1	1		1
12													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
13													1			1			1				1	1		1
14													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
15													1			1			1				1	1		1
16													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
17													1			1			1				1	1		1
18													1			1			1				1	1		1
19													1			1			1				1	1		1
20													1			1			1				1	1		1
21													1			1			1				1	1		1
22													1			1			1				1	1		1
23													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
24													1			1			1				1	1		1
25													1			1			1				1	1		1
26													1			1			1				1	1		1
27													1	2	2	1	2	2	1			2	1	1	2	1
28													1			1			1				1	1		1
29													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
30													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
31													1			1			1				1	1		1
32													1			1			1				1	1		1
33													1			1			1				1	1		1
34													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
35													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
36													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
37													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
38													1			1			1				1	1		1
39													1			1			1				1	1		1

Complications also arose from the analysis techniques:

- some radiochemical analyses involving very low activities gave negative values due to the statistical nature of the measurement technique; these negative values were included in the calculation of the annual mean values, but any annual mean values less than zero were set to zero.
- some IPC-MS analyses involving very low activities gave values below the detection limit; these were set to half the detection limit.

A8.1.1 Estimating the activities of radionuclides not measured at some sites

The following radionuclides:

^{227}Ac, ^{231}Pa, ^{210}Pb, ^{210}Po, ^{228}Ra and ^{230}Th

were not measured at some sampling sites (see Table A8.1). It was found that, at the sites where these radionuclides were measured, the activity values were all very low and varied in a random fashion. The activity of each radionuclide at the sites where measurements were not made was therefore taken to be the mean value for that radionuclide calculated from all the samples at all other sites. The additional doses at the sites where these radionuclides were not measured, resulting from the use of these global mean values, are shown in Table A8.2. The doses are so small that even very large errors will be inconsequential.

Table A8.2 Dose contributions resulting from the use of global mean activity values

Radionuclide	Dose (Msv/a)
Actinium-227	0,0026
Protactinium-231	0,00008
Lead-210	0,0068
Polonium-210	0,0005
Radium-228	0,0088
Thorium-230	0.0005

A8.1.2 Estimating the activities of radionuclides never measured

The following radionuclides:

^{228}Ac, ^{210}Bi, ^{212}Bi, ^{214}Bi, ^{211}Pb, ^{214}Pb, ^{228}Th, ^{231}Th, and ^{234}Th

having very low dose conversion factors, were never measured. The activity concentration of these radionuclides was simply taken to be equal to the mean activity of all measured radionuclides over all sites (0.00672 Bq/ℓ). On the basis of this assumption, the never-measured radionuclides contributed only 0.0005 mSv/a to the dose associated with each sampling site. This was deemed to be sufficiently small a contribution that no further sophistication was justified. For example, even if the activity concentration were to be underestimated by a factor of 3, the dose would be underestimated by only 0.001 mSv/a, a trivial amount.

In practice, the interquartile range (± 0.019 Bq/ℓ) of the mean values of all the measured radionuclides would be a fair first-order estimate of the range of uncertainty of the activity of the never-measured radionuclides. Thus, the uncertainty in the dose contributed by the never-measured radionuclides is 0.0028 mSv/a.

A8.1.3 Extrapolations for radionuclides not measured in phase 1

The following radionuclides:

^{227}Ac, ^{231}Pa, ^{210}Pb, ^{228}Ra, ^{227}Th, ^{230}Th and ^{234}U

were measured only in phase 2 of the study. In an attempt to extrapolate the activities of these radionuclides into the phase 1 period, multilinear regressions were sought against chemical and radiation variables measured during Phase I.

The following procedure was used:

1. To decrease the noise influence of values near the detection limit, all values at or below the detection limit or within one standard deviation of 0, were discarded.

2. Those Phase I variables with relatively few values remaining were discarded.

   It was also found that some of the stations, for example Station1, had exceedingly high (two orders of magnitude) values of certain variables, for example aluminum. Unfortunately, some stations, including Station 1, were dropped from sampling in the second half of the year. Thus including aluminum in the regression variables would result in extrapolating to aluminum values 100 times higher than were calibrated and tested on.

To ensure that this problem did not occur in other variables, the chosen predictors were inspected to ensure that the calibrating stations covered the full range for the variables.

Stations 10 and 2 had exceptionally high values of phosphate and calcium respectively. Phosphate at Station 10 was 5.7 standard deviations above the mean of the other stations. Calcium at Station 2 was 3 standard deviations above the mean of the other stations. Thus Ca and PO4-P were also excluded from the set of possible predictors.

Those variables left were:
Cl, EC, F, gross alpha, gross beta, K, Mg, Na, NH4-N, NO3+NO2-N, pH, Ra-223, Ra-226, Si, SO4, Sr-diss, TAL as CaCO3, TDS, U-235,
U-238.

3. All subsets shorter than 5 of these variables were tested.

4. For each Phase II variable and for each subset of Phase I variables the data was extracted.

5. If there were too few samples to get a good test of the significance of the fit, that subset was rejected.

6. The samples were divided into a calibration set and a test set.

7. The Phase II variable was fitted to the subset of the Phase I variables using the calibration set.

8. The goodness of fit parameter was calculated, using the regression calculated in the previous step, on the both the calibration and the test data sets. The worst value was reported and used in the next step.

9. The subset with the best-reported goodness of fit was selected.

   The goodness of fit parameter was the sum of the squared residuals divided by the number of degrees of freedom, divided by the standard deviation of the variable being fitted i.e. Fitting a subset of length 0, would simply be the mean value of the variable being fitted. The goodness of fit parameter would then simply be 1.

   Thus the goodness of fit tells you how much sharper (if < 1) your prediction is than simply taking the mean value as your predictor. It is never worth selecting a subset for which the goodness of fit parameter, is greater than or equal to 1.

   It was possible, for only two of the Phase II nuclides (Th-227 and U-234), to find a subset of Phase I nuclides which improved our predictive ability. The per station doses are presented in Table 8.3.

Table 8.3 The per station doses.

Site No.	Place	Dose (mSv/year)
29	Turffontein	0,0184
30	Gerhardminnebron	0,0187
14	Gerhardminnebron-Rysmierbult road bridge upstream of Boskop dam	0,0191
35	Potchefstroom purification works-western abstraction point	0,0194
27	Welverdiend municipal water supply 2km south of Welverdiend	0,0206
34	Bovenste Eye	0,0226
6	Wonderfontein Eye-canal from Wonderfontein eye	0,0239
31	Wonderfontein Eye 110 is between piggery buildings	0,0261
26	Plot Welverdiend	0,0268
20	Kraalkop-old Johannesburg/Potchefstroom road bridge	0,0273
25	Plot no 9 Carltonville	0,0286
28	Blaaubank 100m east of house	0,0296
32	Plot 84 De Pan	0,0297
19	Elandsfontein-Johannesburg/Potchefstroom road bridge	0,0299
33	Plot Kraalkop	0,0305
22	Klipdrift dam-outflow into concrete irrigation canal	0,0306
18	Buffelsdoorn-Johannesburg/Potchefstroom road bridge	0,0314
24	Plot 40 Luipaardsvlei - 35m south east of farm house	0,0317
21	Weltevreden-Losberg/bank road bridge	0,0318
6a	West Driefontein (down stream north shaft purification works)	0,0328
36	Potchefstroom purification works-eastern abstraction point	0,0335
38	Varkenslaagte	0,0341
16	Buffelsdoorn-Elandsrand gold mine	0,037
13	Turffontein-gravel road bridge to Muiskraal	0,0423
3	Luipaardsvlei (Doornkop Randfontein (R559) road bridge)	0,0536
10	Blyvooruitzicht gm-discharge to Doornfontn canal east of purification works	0,0563
4	No 7 at Gemsbokfontein	0,0568
2	Rietvlei (Randfontein Azaadville bridge)	0,0591
39	Doornfontein	0,0594
5	Wonderfontein-end of 1m pipe from Venterspost gold mine	0,0653
23	Gempost-Venterspost gold mine no 5 shaft	0,0761
37	Harry's dam	0,0786
8	Wonderfontein-low water bridge to Abe Bailey nature reserve	0,0805
17	Deelkraal-gold mine recreational dam overflow	0,0832
9	Blaauwbank	0,108
11	Doornfontein gold mine-gold plant discharge in canal upstream of Doornfontein excess	0,135
7	Rooipoort	0,155
15	Western Deep levels-farm bridge down stream of no 7 shaft slimes dam	0,178
1	Luipaardsvlei (at rail bridge from Turk shaft to 1st West gold mine	0,24
7a	Carltonville West Driefontein gold mine –Carltonville cemetary road bridge	0,271
12	Doornfontein gold mine-number 3 shaft discharge	0,525

A8.1.4 The Uranium - Dose relationship

Plotting U-238 concentration against yearly dose and performing a least squares linear fit gives us the following relationship...

Dose = 0,0012895 * U + 0,0212758

Correlation coefficient r = 0,99063,

A8.2 Determination of Proportionality Constant F_i

The proportionality constant F_i for radionuclide *i* was determined from the following relationship:

$$F_i = \sum_x C_x (DCF)_{ix} W_x$$

where: C_x is the annual water consumption for age group *x* (ℓ/a)

$(DCF)_{ix}$ is the dose conversion factor for radionuclide *i* and age group *x* (mSv/Bq)

W_x is the weighting factor for age group *x*

The annual water consumption values for the various age groups were taken from CNS Licensing Guide LG-1032[1], and are given in Table A8.3.

Table A8.3 Annual Water Consumption Values

Age Group	Water Consumption (ℓ/a)
0 - 1 years	200
1 - 2 years	260
2 - 7 years	300
7 – 12 years	350
12 - 17 years	600
> 17 years	730

The dose conversion factors for the various radionuclides and age groups were taken from the IAEA Basic Safety Standards[2].

The weighting factor for each age group was determined by dividing the number of years in the age group by the average life expectancy, taken to be 70 years. For example, the weighting factor for the 7 - 12 years age group was:

$$W_{7-12} = \frac{12-7}{70} = 0.0714$$

and for the > 17 years age group:

$$W_{>17} = \frac{70-17}{70} = 0.757$$

The resulting proportionality factors for each radionuclide are listed in Appendix 2 as the 'annual dose per unit activity concentration in water'.

References:

[1] International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, International Atomic Energy Agency, Vienna (1996).

[1] Licensing Guide LG-1032, Guideline on the Assessment of Radiation Hazards to Members of the Public from Mining and Mineral Processing Facilities, Rev. 0, Council for Nuclear Safety, Centurion (18 April 1997)

[2] International Basic Safety Standards for the Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, International Atomic Energy Agency, Vienna (1996)

[2] Licencing Guide LG-1032, Guideline on the Assessment of Radiation Hazards to Members of the Public from Mining and Mineral Processing Facilities, Rev 0, Council for Nuclear Safety, Centurion (1997/04/18).

[3] Detection Limit Concepts: Foundations, Myths, and Utilization, D. A. Chambless et al, Health Physics, volume 63, Number 3, September 1992.

METHOD USED FOR INDEPENDENT DOSE VERIFICATION

A FAANHOF

Appendix 9

METHOD USED FOR INDEPENDENT DOSE VERIFICATION

Evaluation of the Mooi River Catchment Study

1. Assumptions

To enable an "all nuclide" dose calculation the following has been assumed:

- Th-234 and Pa-234m to be in equilibrium with U-238,
- Rn-222, Po-218, Pb-214, Bi-214 and Po-214 to be in equilibrium with Ra-226,
- Bi-210 to be in equilibrium with Pb-210,
- Th-231 to be in equilibrium with U-235,
- Rn-219, Po-215, Pb-211, Bi-211 and Tl-207 are in equilibrium with Ra-223,
- Ac-228 to be in equilibrium with Ra-228, and
- Rn-220, Po-216, Pb-212, Bi-212, Po-212 and Tl-208 in equilibrium with Ra-224.
- Ac-227 at the time of sampling was calculated from two consecutive determinations of Th-227. The results for the three monitoring points surveyed for actinium (18 data) showed a good correlation between these mother-daughter nuclides (with a Th/Ac ratio of 6,12 ± 1,69). Accordingly the activity for the remainder of the samples in the second phase of the survey was estimated from the Th-227 data obtained.
- Pa-231 did not show any direct correlation between the sampling points surveyed for this nuclide and the average concentration observed (0,2 ± 0,9 mBq/L) was taken as the default value for the global mean of the second phase of the Mooi River survey.

2. Dose Calculations and Correlations

According to paragraph one the evaluation has been performed for the most critical groups (i.e. the < 1 year olds followed by the age group between 12 and 17 years old) and the calculated lifetime average exposure. The following calculations were done to allow proper evaluation of the dose received during the one year period and to evaluate the possibility of using one unique monitor for the Mooi River catchment to estimate the yearly dose (instead of doing a full nuclide specific analysis):

- For the second phase of the study the "all nuclide" dose was calculated for the various age groups including the lifetime average dose.
- The same dose calculations were done, now using only the nuclides measured in the first phase of the study (i.e. U-238, U-235, Th-232, Ra-226, Ra-224 and Ra-223).
- We then determined the linear regression between these two calculated doses (i.e. the so-called "all nuclide" dose and the "phase 1" nuclide dose). The correlation obtained for "Lifetime average" use was:
  [All nuclide dose] = 1,109 x [Phase 1 nuclides dose] + 0,017 (R^2 = 0,980)
- The "phase 1" nuclide dose was then calculated for the same eighteen monitoring points surveyed in phase 1 of the study, and using the above correlations the "all nuclide" dose for these monitoring points was calculated.
- From the two sets of data (i.e. the "all nuclide" dose for the first and the second semester of 1997 for the eighteen corresponding sites; with the omission of one point that dried up during the second phase) the average ratio of the phase 1 to phase 2 "all nuclide" dose was calculated. This ratio was used to determine the "all nuclide" dose during phase 2 for the monitoring sites not surveyed in the second phase of the study. The average "all nuclide" dose was calculated, accordingly, from the phase 1 and phase 2 data. The results are shown in Table A for the lifetime average evaluation, the age group between 12 and 17 year old and the age groups of < 1 year old respectively.
- From the uranium data of the corresponding eighteen monitoring sites surveyed in both the first and the second semester of 1997 the average ratio of the phase 1 to phase 2 uranium concentrations (in µg/L) was calculated. This ratio was used to determine the uranium concentration during phase 2 for those monitoring sites not surveyed in the second phase of the study. From the phase 1 and phase 2 data the average uranium concentration was calculated.

Table A: Average Analytical Results (Based on phase-2 radioanalytical data)

Mooi River Catchment Study: January to December 1997

Yearly dose for Members of the Public (mSv/a) and Uranium concentration

	Life-time average dose (mSv/a) *				Age group 12 - 17 year dose (mSv/a) *				Age group < 1 year dose (mSv/a) *				[U] (ug/L) *			
	Phase 1	Phase 2	Average	p1/p2 Ratio	Phase 1	Phase 2	Average	p1/p2 Ratio	Phase 1	Phase 2	Average	p1/p2 Ratio	Phase 1	Phase 2	Average	p1/p2 Ratio
DWAF-1	**0.228**	0.228	0.228	1.00	**0.539**	0.514	0.526	1.05	**0.826**	0.742	0.784	1.11	**156.54**	159.99	158.27	0.98
DWAF-2	**0.047**	0.047	0.047	1.00	**0.100**	0.095	0.098	1.05	**0.179**	0.160	0.170	1.11	**20.50**	20.95	20.72	0.98
DWAF-3	**0.053**	**0.066**	**0.060**	**0.80**	**0.084**	**0.095**	**0.089**	**0.89**	**0.182**	**0.170**	**0.176**	**1.07**	**36.18**	**55.52**	**45.85**	**0.65**
DWAF-4	**0.055**	0.055	0.055	1.00	**0.092**	0.087	0.090	1.05	**0.183**	0.165	0.174	1.11	**38.28**	39.13	38.71	0.98
DWAF-5	**0.052**	**0.052**	**0.052**	**1.01**	**0.090**	**0.080**	**0.085**	**1.13**	**0.188**	**0.163**	**0.176**	**1.16**	**31.38**	**36.95**	**34.16**	**0.85**
DWAF-6	**0.024**	**0.018**	**0.021**	**1.35**	**0.044**	**0.033**	**0.039**	**1.34**	**0.096**	**0.060**	**0.078**	**1.60**	**3.14**	**3.95**	**3.55**	**0.79**
DWAF-6a	**0.024**	0.024	0.024	1.00	**0.046**	0.044	0.045	1.05	**0.098**	0.088	0.093	1.11	**3.19**	3.26	3.22	0.98
DWAF-7	**0.158**	**0.133**	**0.145**	**1.19**	**0.315**	**0.190**	**0.252**	**1.66**	**0.515**	**0.355**	**0.435**	**1.45**	**128.56**	**123.79**	**126.17**	**1.04**
DWAF-7a	**0.252**	**0.238**	**0.245**	**1.06**	**0.510**	**0.378**	**0.444**	**1.35**	**0.805**	**0.702**	**0.754**	**1.15**	**214.71**	**213.09**	**213.90**	**1.01**
DWAF-8	**0.076**	0.076	0.076	1.00	**0.133**	0.127	0.130	1.05	**0.248**	0.223	0.235	1.11	**58.77**	60.07	59.42	0.98
DWAF-9	**0.101**	**0.113**	0.107	0.89	**0.205**	0.165	0.185	1.24	**0.341**	0.309	0.325	1.11	**73.39**	102.15	87.77	0.72
DWAF-10	**0.051**	0.051	0.051	1.00	**0.109**	0.104	0.106	1.05	**0.190**	0.171	0.180	1.11	**23.24**	23.75	23.50	0.98
DWAF-11	**0.130**	0.130	0.130	1.00	**0.303**	0.288	0.295	1.05	**0.465**	0.417	0.441	1.11	**84.07**	85.92	85.00	0.98
DWAF-12	**0.476**	**0.164**	**0.320**	**2.91**	**1.295**	**0.301**	**0.798**	**4.30**	**1.755**	**0.623**	**1.189**	**2.82**	**276.61**	**126.21**	**201.41**	**2.19**
DWAF-13	**0.036**	0.036	0.036	1.00	**0.060**	0.057	0.058	1.05	**0.129**	0.116	0.123	1.11	**18.78**	19.19	18.99	0.98
DWAF-14	**0.022**	**0.012**	**0.017**	**1.85**	**0.034**	**0.022**	**0.028**	**1.53**	**0.089**	**0.038**	**0.063**	**2.36**	**2.88**	**3.79**	**3.33**	**0.76**
DWAF-15	**0.191**	0.191	0.191	1.00	**0.488**	0.465	0.477	1.05	**0.701**	0.630	0.665	1.11	**114.00**	116.52	115.26	0.98
DWAF-16	**0.042**	**0.034**	**0.038**	**1.21**	**0.073**	**0.056**	**0.064**	**1.30**	**0.148**	**0.101**	**0.124**	**1.47**	**22.83**	**23.84**	**23.34**	**0.96**
DWAF-17	**0.081**	0.081	0.081	1.00	**0.157**	0.150	0.154	1.05	**0.272**	0.244	0.258	1.11	**58.16**	59.44	58.80	0.98
DWAF-18	**0.024**	0.024	0.024	1.00	**0.042**	0.040	0.041	1.05	**0.095**	0.086	0.090	1.11	**3.99**	4.07	4.03	0.98
DWAF-19	**0.022**	0.022	0.022	1.00	**0.037**	0.036	0.036	1.05	**0.089**	0.080	0.084	1.11	**2.96**	3.03	2.99	0.98
DWAF-20	**0.019**	0.019	0.019	1.00	**0.031**	0.029	0.030	1.05	**0.079**	0.071	0.075	1.11	**0.57**	0.58	0.57	0.98
DWAF-21	**0.025**	0.025	0.025	1.00	**0.040**	0.038	0.039	1.05	**0.095**	0.085	0.090	1.11	**7.33**	7.49	7.41	0.98
DWAF-22	**0.023**	0.023	0.023	1.00	**0.035**	0.034	0.035	1.05	**0.090**	0.081	0.086	1.11	**5.06**	5.18	5.12	0.98
DWAF-23	**0.052**	**0.055**	**0.054**	**0.94**	**0.124**	**0.116**	**0.120**	**1.08**	**0.203**	**0.191**	**0.197**	**1.07**	**19.69**	**28.97**	**24.33**	**0.68**
DWAF-24	**0.024**	0.024	0.024	1.00	**0.052**	0.049	0.051	1.05	**0.102**	0.092	0.097	1.11	**0.66**	0.67	0.66	0.98
DWAF-25	**0.021**	0.021	0.021	1.00	**0.037**	0.035	0.036	1.05	**0.086**	0.078	0.082	1.11	**0.78**	0.79	0.78	0.98
DWAF-26	**0.018**	0.018	0.018	1.00	**0.026**	0.025	0.025	1.05	**0.074**	0.066	0.070	1.11	**0.75**	0.76	0.76	0.98
DWAF-27	**0.020**	**0.018**	**0.019**	**1.15**	**0.028**	**0.033**	**0.031**	**0.85**	**0.086**	**0.073**	**0.079**	**1.17**	**1.00**	**0.46**	**0.73**	**2.14**
DWAF-28	**0.021**	0.021	0.021	1.00	**0.029**	0.027	0.028	1.05	**0.092**	0.083	0.087	1.11	**1.58**	1.61	1.60	0.98
DWAF-29	**0.019**	**0.023**	**0.021**	**0.82**	**0.026**	**0.032**	**0.029**	**0.81**	**0.075**	**0.106**	**0.091**	**0.70**	**0.94**	**1.08**	**1.01**	**0.87**
DWAF-30	**0.018**	**0.016**	**0.017**	**1.15**	**0.024**	**0.028**	**0.026**	**0.87**	**0.072**	**0.068**	**0.070**	**1.07**	**0.53**	**0.31**	**0.42**	**1.71**
DWAF-31	**0.018**	0.018	0.018	1.00	**0.025**	0.024	0.024	1.05	**0.075**	0.067	0.071	1.11	**0.44**	0.45	0.44	0.98
DWAF-32	**0.021**	0.021	0.021	1.00	**0.037**	0.035	0.036	1.05	**0.087**	0.078	0.082	1.11	**1.00**	1.02	1.01	0.98
DWAF-33	**0.022**	0.022	0.022	1.00	**0.041**	0.039	0.040	1.05	**0.092**	0.083	0.088	1.11	**1.56**	1.60	1.58	0.98
DWAF-34	**0.018**	**0.027**	**0.022**	**0.69**	**0.025**	**0.044**	**0.034**	**0.57**	**0.074**	**0.104**	**0.089**	**0.71**	**0.81**	**1.26**	**1.04**	**0.64**
DWAF-35	**0.020**	**0.034**	**0.027**	**0.58**	**0.028**	**0.043**	**0.035**	**0.65**	**0.077**	**0.156**	**0.116**	**0.49**	**1.88**	**3.01**	**2.45**	**0.62**
DWAF-36	**0.022**	**0.041**	**0.032**	**0.55**	**0.034**	**0.054**	**0.044**	**0.62**	**0.086**	**0.196**	**0.141**	**0.44**	**4.91**	**3.08**	**3.99**	**1.59**
DWAF-37	**0.071**	**0.097**	**0.084**	**0.73**	**0.127**	**0.140**	**0.133**	**0.91**	**0.232**	**0.287**	**0.259**	**0.81**	**52.72**	**84.90**	**68.81**	**0.62**
DWAF-38	**0.031**	0.031	0.031	1.00	**0.048**	0.046	0.047	1.05	**0.110**	0.099	0.105	1.11	**13.96**	14.27	14.11	0.98
DWAF-39	**0.053**	0.053	0.053	1.00	**0.119**	0.114	0.117	1.05	**0.198**	0.178	0.188	1.11	**24.01**	24.54	24.27	0.98
Average				1.00				1.05				1.11				0.98

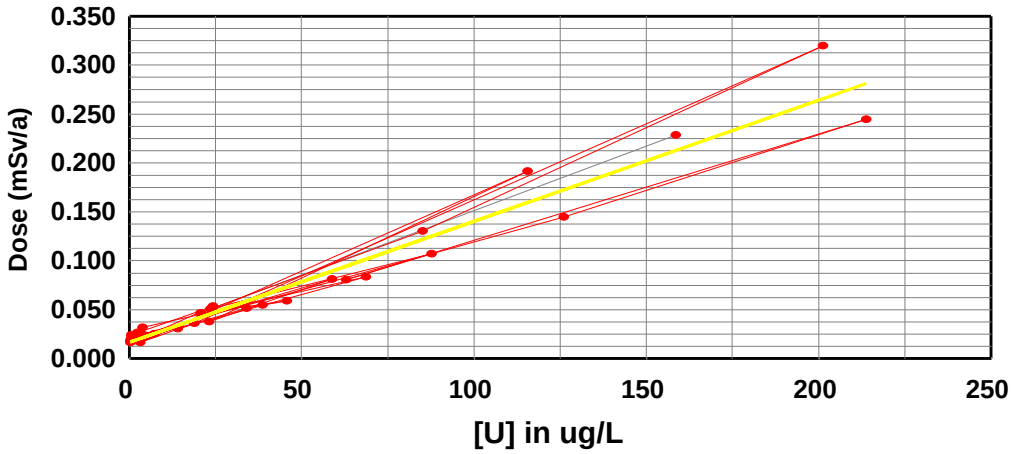
* **Measured data printed in bold. Other data estimated from global means of measured data**

- Thereafter, the linear regression between the average uranium concentration and the average “all nuclide” dose was calculated, using all monitoring sites in the evaluation. The following correlations were obtained, the last correlation being graphically represented in Graph A.

< 1 year old: [All nuclide dose] (mSv/a) = 0,00409 x [U] (µg/L) + 0,063 (R^2 = 0,932)
12 - 17 year old:[All nuclide dose] (mSv/a) = 0,00275 x [U] (µg/L) + 0,020 (R^2 = 0,901)
Lifetime average:[All nuclide dose] (mSv/a) = 0,00124 x [U] (µg/L) + 0,017 (R^2 = 0,970)

Yearly Dose vs [Uranium]

Mooi River Catchment (1997)



APPENDIX 10
ESTIMATION OF THE POSSIBLE UNCERTAINTIES

Appendix 10

ESTIMATION OF THE POSSIBLE UNCERTAINTIES

Possible uncertainties in the estimation of the yearly dose received from drinking environmental (untreated) water in the Mooi River catchment will arise from analytical uncertainties, environmental variations, the applied uranium to dose correlation curve, the age dependant default intake values and the sampling frequency.

- The analytical uncertainty can be estimated from the uranium results obtained in the second phase study by both the radiochemical and ICP-MS analysis techniques. The correlations between the uranium concentration and the "all nuclide" dose described in paragraph 5 have been determined using the radiochemical uranium database. The same evaluation based on the ICP-MS uranium data showed the following correlations:
  - < 1 year old: [All nuclide dose] (mSv/a) = 0,00415 x [U] (µg/L) + 0,065 (R^2 = 0,922).
  - 12 - 17 year old: [All nuclide dose] (mSv/a) = 0,00273 x [U] (µg/L) + 0,024 (R^2 = 0,889).
  - Lifetime average: [All nuclide dose] (mSv/a) = 0,00124 x [U] (µg/L) + 0,017 (R^2 = 0,964).
- These data compare well with the correlation observed from the radiochemical uranium determination. The difference in the calculated dose based on radiochemical and ICP-MS analysis at a dose level of 75 µSv/a is about 2%, 4% and 1,5% for the respective age groups of < 1 year old, between 12 and 17 years old and the lifetime average evaluation. Table B provides the summed data on the linear regression and dose calculations.
- Environmental variations can be estimated from the standard deviation observed for the individual nuclide analyses in phase 1 and phase 2 of the study. Again the total yearly dose correlation has been calculated, now using the "upper" and "lower" bound regions of the analytical data (i.e. the average concentrations plus and minus one standard deviation respectively). The correlations were determined using both the Radiochemical and ICP-MS uranium data sets obtained in phase 2 of the study. Once more, both sets did not show substantial differences and accordingly the mean values were taken to evaluate the yearly fluctuation in the dose. The data for the critical groups (i.e. the < 1 year old followed by the age group between 12 and 17 years old) and the lifetime averages are shown in Table C. From this it may be observed that at around an estimated average yearly dose of 100 µSv/a the "upper" limits of the evaluated dose will not vary more than about 20%, 30% and 50% for the respective lifetime average evaluation and the age groups 12 to 17 years old and < 1 year old. This shows that the calculated yearly dose based on average yearly nuclide concentrations will provide a fair estimation of the radiological impact on the public.
- The applied uranium to dose correlation curve will show a slight variation if sampling sites would be randomly omitted from the regression calculations. This uncertainty will be less than 10% due to the high degree of correlation between the measured uranium concentration and the estimated yearly dose. Omission of sampling site 12 which dried up during the second phase of the survey, showing high nuclide concentrations during the first phase, will cause a difference of plus 6% in the calculated dose levels around 100 µSv/a, while the omission of the sampling site showing the highest average uranium concentration during the monitoring period will give a 3% negative deviation at about 100 µSv/a (see Table D). The expected uncertainty in the obtained correlation between the yearly dose and the uranium concentration for the Mooi River catchment will be less than 10%, provided statistically reliable average uranium data are obtained (e.g. through monthly monitoring).

- The age dependent default intake values are prone to a large uncertainty in the yearly dose evaluation. It should be emphasized that default intake rates are used in the dose calculations, i.e. assuming daily intake from the same source and assuming that the source is the only available source to the individuals concerned. Accordingly, at sites showing potentially elevated dose levels (e.g. above 100 µSv/a) due to default water

intake one should determine the actual yearly consumption from the source by the communities and/or individuals concerned.

- The influence of the sampling frequency on the calculated yearly dose can be estimated best from the uranium data obtained in phase 1 on the Mooi River catchment study. The average concentrations were calculated for the individual sites together with the four-weekly average, shifting the intervals by one week respectively. One would thus obtain the average concentrations for uranium at the following four intervals:

  Weeks 1, 5, 9, 13, 17, 21
  Weeks 2, 6, 10, 14, 18, 22
  Weeks 3, 7, 11, 15, 19, 23
  Weeks 4, 8, 12, 16, 20, 24

  Comparison of the minimum and maximum difference between these individual data and the average concentration observed over the entire sampling period provides an estimate of the possible over- or underestimation of the uranium concentration. In this model the sites not sampled at a particular date were regarded as not being accessible, although for dose calculations one should "dry" sites regard as having zero uranium concentration as they are not contributing to the yearly dose at that specific time. Table E shows the compiled data for phase 1 and the observed uranium ratio between phase 1 and phase 2. The following observations are made:

  - Four-weekly sampling compared to weekly sampling can over- or underestimate the yearly dose by a factor of up to 3. (Site 38 being discarded due to infrequent sampling).
  - The data obtained in the second phase can not clearly be related to seasonal influences. Sampling sites 35 and 36 show increased levels of uranium during the second semester not readily explained by sampling frequency variations. Sampling site 12 showed a decreased uranium content in the second phase of the study; this site dried up due to decreased/ceased input of waste water directly related to the gold mining activities.

Conclusions

- The correlations observed in paragraphs 5 and 8 between the uranium concentration (in µg/L) or the gross activity (in Bq/L) and the "all nuclide" yearly dose (in mSv/a) can be used for routine monitoring purposes of the Mooi River catchment area.
- The estimated uncertainty will be less than 10%.
- The proposed monitoring frequency is monthly for uranium and every six months for the full range of nuclides to evaluate whether the correlation is sustainable and to reduce the uncertainty due to sampling frequency.

References

(1) IAEA, Safety Series 115, Vienna, 1996.
(2) CNS, Document LG-1032, Centurion, 1997.

Table B: Yearly dose versus Uranium concentration for the 1997 Mooi River catchment survey

Average seasonal concentrations

Life-time Average

Regression Output: Rad Chem

Constant	**0.01665**
Std Err of Y Est	0.0130582
R Squared	**0.97028**
No. of Observations	41
Degrees of Freedom	39
X Coefficient(s)	**0.00124**
Std Err of Coef.	3.469E-05

Regression Output: ICP-MS

Constant	**0.0174**
Std Err of Y Est	0.0142338
R Squared	**0.96403**
No. of Observations	41
Degrees of Freedom	39
X Coefficient(s)	**0.00124**
Std Err of Coef.	3.85E-05

12 – 17 a

Regression Output: Rad Chem

Constant	**0.02023**
Std Err of Y Est	0.0548189
R Squared	**0.90147**
No. of Observations	41
Degrees of Freedom	39
X Coefficient(s)	**0.002751**
Std Err of Coef.	0.0001456

Regression Output: ICP-MS

Constant	**0.02395**
Std Err of Y Est	0.0571486
R Squared	**0.8887**
No. of Observations	41
Degrees of Freedom	39
X Coefficient(s)	**0.002728**
Std Err of Coef.	0.0001546

< 1 a

Regression Output: Rad Chem

Constant	**0.06324**
Std Err of Y Est	0.06663
R Squared	**0.93205**
No. of Observations	41
Degrees of Freedom	39
X Coefficient(s)	**0.00409**
Std Err of Coef.	0.000177

Regression Output: ICP-MS

Constant	**0.06458**
Std Err of Y Est	0.071467
R Squared	**0.92188**
No. of Observations	41
Degrees of Freedom	39
X Coefficient(s)	**0.00415**
Std Err of Coef.	0.0001933

[U] (ug/L)	Yearly dose (mSv/a) RadChem	ICP-MS	Ratio
5	0.023	0.024	0.967
25	0.048	0.049	0.981
50	0.079	0.080	0.986
75	0.109	0.111	0.989
100	0.140	0.142	0.990
125	0.171	0.173	0.991
150	0.202	0.204	0.991
175	0.233	0.235	0.992
200	0.264	0.266	0.992
225	0.295	0.297	0.992
250	0.326	0.329	0.993
275	0.357	0.360	0.993
300	0.388	0.391	0.993
325	0.419	0.422	0.993
350	0.450	0.453	0.993
375	0.481	0.484	0.993
400	0.512	0.515	0.993
425	0.543	0.546	0.993
450	0.574	0.577	0.994
475	0.605	0.609	0.994
500	0.636	0.640	0.994
525	0.667	0.671	0.994
550	0.698	0.702	0.994
575	0.728	0.733	0.994
600	0.759	0.764	0.994
625	0.790	0.795	0.994
650	0.821	0.826	0.994
675	0.852	0.858	0.994
700	0.883	0.889	0.994
725	0.914	0.920	0.994
750	0.945	0.951	0.994
775	0.976	0.982	0.994
800	1.007	1.013	0.994
825	1.038	1.044	0.994
850	1.069	1.075	0.994
875	1.100	1.106	0.994
900	1.131	1.138	0.994
925	1.162	1.169	0.994
950	1.193	1.200	0.994
975	1.224	1.231	0.994
1000	1.255	1.262	0.994

[U] (ug/L)	Yearly dose (mSv/a) RadChem	ICP-MS	Ratio
5	0.034	0.038	0.904
25	0.089	0.092	0.966
50	0.158	0.160	0.984
75	0.227	0.229	0.991
100	0.295	0.297	0.995
125	0.364	0.365	0.998
150	0.433	0.433	1.000
175	0.502	0.501	1.001
200	0.570	0.569	1.002
225	0.639	0.638	1.002
250	0.708	0.706	1.003
275	0.777	0.774	1.004
300	0.846	0.842	1.004
325	0.914	0.910	1.004
350	0.983	0.979	1.005
375	1.052	1.047	1.005
400	1.121	1.115	1.005
425	1.189	1.183	1.005
450	1.258	1.251	1.005
475	1.327	1.320	1.006
500	1.396	1.388	1.006
525	1.465	1.456	1.006
550	1.533	1.524	1.006
575	1.602	1.592	1.006
600	1.671	1.661	1.006
625	1.740	1.729	1.006
650	1.808	1.797	1.006
675	1.877	1.865	1.006
700	1.946	1.933	1.007
725	2.015	2.001	1.007
750	2.083	2.070	1.007
775	2.152	2.138	1.007
800	2.221	2.206	1.007
825	2.290	2.274	1.007
850	2.359	2.342	1.007
875	2.427	2.411	1.007
900	2.496	2.479	1.007
925	2.565	2.547	1.007
950	2.634	2.615	1.007
975	2.702	2.683	1.007
1000	2.771	2.752	1.007

[U] (ug/L)	Yearly dose (mSv/a) RadChem	ICP-MS	Ratio
5	0.084	0.085	0.981
25	0.166	0.168	0.984
50	0.268	0.272	0.985
75	0.370	0.376	0.986
100	0.473	0.479	0.986
125	0.575	0.583	0.986
150	0.677	0.687	0.987
175	0.780	0.790	0.987
200	0.882	0.894	0.987
225	0.984	0.998	0.987
250	1.087	1.101	0.987
275	1.189	1.205	0.987
300	1.291	1.309	0.987
325	1.394	1.412	0.987
350	1.496	1.516	0.987
375	1.599	1.620	0.987
400	1.701	1.723	0.987
425	1.803	1.827	0.987
450	1.906	1.931	0.987
475	2.008	2.034	0.987
500	2.110	2.138	0.987
525	2.213	2.242	0.987
550	2.315	2.345	0.987
575	2.417	2.449	0.987
600	2.520	2.553	0.987
625	2.622	2.656	0.987
650	2.724	2.760	0.987
675	2.827	2.864	0.987
700	2.929	2.967	0.987
725	3.032	3.071	0.987
750	3.134	3.175	0.987
775	3.236	3.278	0.987
800	3.339	3.382	0.987
825	3.441	3.486	0.987
850	3.543	3.589	0.987
875	3.646	3.693	0.987
900	3.748	3.797	0.987
925	3.850	3.900	0.987
950	3.953	4.004	0.987
975	4.055	4.108	0.987
1000	4.157	4.211	0.987

Table C: Evaluation of the Upper, Average and Lower Uranium concentration to estimate seasonal variations

Life-time Average						12 - 17 a						< 1 a					
[U]	Yearly dose (mSv/a)					[U]	Yearly dose (mSv/a)					[U]	Yearly dose (mSv/a)				
(ug/L)	Upper	Average	Lower	U/A Ratio	A/L Ratio	(ug/L)	Upper	Average	Lower	U/A Ratio	A/L Ratio	(ug/L)	Upper	Average	Lower	U/A Ratio	A/L Ratio
5	0.036	0.023	0.005	1.53	4.41	5	0.062	0.036	0.011	1.72	3.37	5	0.152	0.085	0.005	1.79	17.77
25	0.063	0.048	0.027	1.31	1.75	25	0.122	0.091	0.052	1.35	1.76	25	0.247	0.167	0.069	1.48	2.42
50	0.097	0.079	0.055	1.23	1.43	50	0.197	0.159	0.103	1.24	1.55	50	0.367	0.270	0.149	1.36	1.81
75	0.132	0.110	0.083	1.20	1.33	75	0.273	0.228	0.154	1.20	1.48	75	0.487	0.373	0.230	1.31	1.62
100	0.166	0.141	0.111	1.18	1.28	100	0.348	0.296	0.205	1.18	1.44	100	0.607	0.476	0.310	1.27	1.54
125	0.200	0.172	0.138	1.16	1.24	125	0.423	0.365	0.256	1.16	1.42	125	0.726	0.579	0.390	1.25	1.48
150	0.235	0.203	0.166	1.15	1.22	150	0.499	0.433	0.307	1.15	1.41	150	0.846	0.682	0.471	1.24	1.45
175	0.269	0.234	0.194	1.15	1.21	175	0.574	0.501	0.359	1.15	1.40	175	0.966	0.785	0.551	1.23	1.42
200	0.303	0.265	0.222	1.14	1.20	200	0.650	0.570	0.410	1.14	1.39	200	1.086	0.888	0.631	1.22	1.41
225	0.338	0.296	0.249	1.14	1.19	225	0.725	0.638	0.461	1.14	1.39	225	1.205	0.991	0.712	1.22	1.39
250	0.372	0.327	0.277	1.14	1.18	250	0.800	0.707	0.512	1.13	1.38	250	1.325	1.094	0.792	1.21	1.38
275	0.406	0.358	0.305	1.13	1.18	275	0.876	0.775	0.563	1.13	1.38	275	1.445	1.197	0.872	1.21	1.37
300	0.441	0.389	0.333	1.13	1.17	300	0.951	0.844	0.614	1.13	1.37	300	1.565	1.300	0.953	1.20	1.36
325	0.475	0.420	0.360	1.13	1.17	325	1.026	0.912	0.666	1.13	1.37	325	1.684	1.403	1.033	1.20	1.36
350	0.509	0.451	0.388	1.13	1.16	350	1.102	0.981	0.717	1.12	1.37	350	1.804	1.506	1.113	1.20	1.35
375	0.544	0.483	0.416	1.13	1.16	375	1.177	1.049	0.768	1.12	1.37	375	1.924	1.609	1.194	1.20	1.35
400	0.578	0.514	0.444	1.13	1.16	400	1.253	1.118	0.819	1.12	1.36	400	2.044	1.712	1.274	1.19	1.34
425	0.612	0.545	0.471	1.12	1.16	425	1.328	1.186	0.870	1.12	1.36	425	2.163	1.815	1.354	1.19	1.34
450	0.646	0.576	0.499	1.12	1.15	450	1.403	1.255	0.922	1.12	1.36	450	2.283	1.918	1.434	1.19	1.34
475	0.681	0.607	0.527	1.12	1.15	475	1.479	1.323	0.973	1.12	1.36	475	2.403	2.021	1.515	1.19	1.33
500	0.715	0.638	0.555	1.12	1.15	500	1.554	1.392	1.024	1.12	1.36	500	2.523	2.124	1.595	1.19	1.33
525	0.749	0.669	0.582	1.12	1.15	525	1.629	1.460	1.075	1.12	1.36	525	2.642	2.227	1.675	1.19	1.33
550	0.784	0.700	0.610	1.12	1.15	550	1.705	1.529	1.126	1.12	1.36	550	2.762	2.330	1.756	1.19	1.33
575	0.818	0.731	0.638	1.12	1.15	575	1.780	1.597	1.177	1.11	1.36	575	2.882	2.433	1.836	1.18	1.33
600	0.852	0.762	0.666	1.12	1.14	600	1.856	1.666	1.229	1.11	1.36	600	3.002	2.536	1.916	1.18	1.32
625	0.887	0.793	0.693	1.12	1.14	625	1.931	1.734	1.280	1.11	1.36	625	3.121	2.639	1.997	1.18	1.32
650	0.921	0.824	0.721	1.12	1.14	650	2.006	1.803	1.331	1.11	1.35	650	3.241	2.742	2.077	1.18	1.32
675	0.955	0.855	0.749	1.12	1.14	675	2.082	1.871	1.382	1.11	1.35	675	3.361	2.845	2.157	1.18	1.32
700	0.990	0.886	0.776	1.12	1.14	700	2.157	1.940	1.433	1.11	1.35	700	3.481	2.948	2.238	1.18	1.32
725	1.024	0.917	0.804	1.12	1.14	725	2.232	2.008	1.484	1.11	1.35	725	3.600	3.051	2.318	1.18	1.32
750	1.058	0.948	0.832	1.12	1.14	750	2.308	2.077	1.536	1.11	1.35	750	3.720	3.154	2.398	1.18	1.32
775	1.093	0.979	0.860	1.12	1.14	775	2.383	2.145	1.587	1.11	1.35	775	3.840	3.257	2.479	1.18	1.31
800	1.127	1.010	0.887	1.12	1.14	800	2.459	2.214	1.638	1.11	1.35	800	3.960	3.360	2.559	1.18	1.31
825	1.161	1.041	0.915	1.12	1.14	825	2.534	2.282	1.689	1.11	1.35	825	4.079	3.463	2.639	1.18	1.31
850	1.196	1.072	0.943	1.12	1.14	850	2.609	2.350	1.740	1.11	1.35	850	4.199	3.566	2.720	1.18	1.31
875	1.230	1.103	0.971	1.11	1.14	875	2.685	2.419	1.791	1.11	1.35	875	4.319	3.669	2.800	1.18	1.31
900	1.264	1.134	0.998	1.11	1.14	900	2.760	2.487	1.843	1.11	1.35	900	4.439	3.772	2.880	1.18	1.31
925	1.298	1.165	1.026	1.11	1.14	925	2.836	2.556	1.894	1.11	1.35	925	4.558	3.875	2.961	1.18	1.31
950	1.333	1.196	1.054	1.11	1.14	950	2.911	2.624	1.945	1.11	1.35	950	4.678	3.978	3.041	1.18	1.31
975	1.367	1.227	1.082	1.11	1.13	975	2.986	2.693	1.996	1.11	1.35	975	4.798	4.081	3.121	1.18	1.31
1000	1.401	1.258	1.109	1.11	1.13	1000	3.062	2.761	2.047	1.11	1.35	1000	4.918	4.184	3.202	1.18	1.31

Table D: Uncertainty in the yearly dose versus uranium concentration

[U] (ug/L)	Yearly dose (mSv/a) Based on Radiochemical uranium data			Ratio	
	All points	All except DWAF 12	All except DWAF 7a	All vs 12 exemption	All vs 7a exemption
5	0.023	0.024	0.022	0.94	1.02
25	0.048	0.047	0.048	1.01	0.99
50	0.079	0.075	0.080	1.04	0.98
75	0.109	0.103	0.112	1.06	0.97
100	0.140	0.132	0.145	1.07	0.97
125	0.171	0.160	0.177	1.07	0.97
150	0.202	0.188	0.209	1.07	0.97
175	0.233	0.217	0.241	1.08	0.97
200	0.264	0.245	0.273	1.08	0.97
225	0.295	0.273	0.306	1.08	0.97
250	0.326	0.301	0.338	1.08	0.97
275	0.357	0.330	0.370	1.08	0.97
300	0.388	0.358	0.402	1.08	0.97
325	0.419	0.386	0.434	1.09	0.96
350	0.450	0.414	0.466	1.09	0.96
375	0.481	0.443	0.499	1.09	0.96
400	0.512	0.471	0.531	1.09	0.96
425	0.543	0.499	0.563	1.09	0.96
450	0.574	0.527	0.595	1.09	0.96
475	0.605	0.556	0.627	1.09	0.96
500	0.636	0.584	0.659	1.09	0.96
525	0.667	0.612	0.692	1.09	0.96
550	0.698	0.640	0.724	1.09	0.96
575	0.728	0.669	0.756	1.09	0.96
600	0.759	0.697	0.788	1.09	0.96
625	0.790	0.725	0.820	1.09	0.96
650	0.821	0.753	0.853	1.09	0.96
675	0.852	0.782	0.885	1.09	0.96
700	0.883	0.810	0.917	1.09	0.96
725	0.914	0.838	0.949	1.09	0.96
750	0.945	0.866	0.981	1.09	0.96
775	0.976	0.895	1.013	1.09	0.96
800	1.007	0.923	1.046	1.09	0.96
825	1.038	0.951	1.078	1.09	0.96
850	1.069	0.979	1.110	1.09	0.96
875	1.100	1.008	1.142	1.09	0.96
900	1.131	1.036	1.174	1.09	0.96
925	1.162	1.064	1.206	1.09	0.96
950	1.193	1.092	1.239	1.09	0.96
975	1.224	1.121	1.271	1.09	0.96
1000	1.255	1.149	1.303	1.09	0.96

Table E: Sampling frequency influence

Variation between weekly and 4-weekly sampling

Sample		Average [U] (ug/L)	Dose Underestimate Min deviation	Dose Overestimate Max deviation	Ph1/Ph2 [U] Ratio	Inverse Min
38		9.31	0.04	2.63	0.90	23.69
28		1.26	0.32	3.59	0.90	3.11
33		1.06	0.38	2.55	0.90	2.66
15		114.00	0.46	1.31	0.90	2.17
22		5.06	0.49	1.58	0.90	2.04
13		18.78	0.50	2.27	0.90	2.02
29		**0.94**	**0.50**	**1.77**	**1.42**	**2.00**
18		3.99	0.53	1.39	0.90	1.90
34		**0.78**	**0.55**	**2.41**	**1.40**	**1.81**
37		**48.33**	**0.57**	**1.35**	**1.24**	**1.76**
32		0.96	0.59	2.18	0.90	1.71
14		**2.88**	**0.62**	**1.76**	**0.42**	**1.61**
11		84.07	0.63	1.59	0.90	1.58
26		0.63	0.64	2.37	0.90	1.55
27		**0.92**	**0.64**	**1.74**	**0.85**	**1.55**
7		**128.56**	**0.66**	**1.24**	**0.69**	**1.51**
25		0.62	0.67	2.56	0.90	1.49
16		**21.01**	**0.69**	**2.38**	**0.68**	**1.44**
36		**12.80**	**0.71**	**1.73**	**2.29**	**1.41**
23		**18.91**	**0.73**	**1.21**	**0.94**	**1.37**
30		**0.53**	**0.74**	**1.44**	**0.94**	**1.34**
6	a	3.19	0.75	1.25	0.90	1.33
10		23.24	0.75	1.26	0.90	1.32
39		22.01	0.77	1.40	0.90	1.30
8		58.77	0.77	1.36	0.90	1.30
24		0.52	0.79	1.52	0.90	1.26
35		**1.55**	**0.81**	**1.30**	**2.02**	**1.23**
7	a	**214.71**	**0.84**	**1.22**	**0.87**	**1.18**
20		0.57	0.85	1.23	0.90	1.18
6		**3.14**	**0.85**	**1.19**	**0.62**	**1.17**
5		**31.38**	**0.85**	**1.18**	**0.87**	**1.17**
12		**243.42**	**0.88**	**1.36**	**0.35**	**1.13**
2		20.50	0.88	1.23	0.90	1.13
3		**36.18**	**0.91**	**1.06**	**0.93**	**1.10**
21		7.33	0.91	1.16	0.90	1.10
1		156.54	0.93	1.09	0.90	1.07
31		0.42	0.94	1.13	0.90	1.07
19		2.96	0.94	1.19	0.90	1.06
9		**73.39**	**0.95**	**1.05**	**0.90**	**1.05**
17		48.85	0.99	1.60	0.90	1.01
4		38.28	0.99	1.02	0.90	1.01

* Data printed in bold are measured, others are estimated from the "global" mean