DEPARTMENT OF WATER AFFAIRS AND FORESTRY

Institute for Water Quality Studies

RADIOACTIVITY DOSE CALCULATION AND WATER QUALITY EVALUATION GUIDELINE FOR DOMESTIC WATER USE

March 2002

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Foreword

While radioactivity in water is relatively easily measured, given the appropriate equipment and radio-analytical expertise, the interpretation of the significance of the measured radioactivity to the domestic water user is beset with uncertainties and imponderables, especially when it comes to evaluating the actual risk to the consumer. There are many reasons for this, a basic one being that the dose-effect response assumes large statistical error-bars and indeterminacy when one extrapolates to the typically minimal radioactivity condition found in most water samples. The international criteria for radioactivity in drinking water present a plethora of different approaches, and are not very helpful in this regard.

The international approach to drinking water radioactivity has tended to focus on one or two selected radioactive nuclides in water, and has not offered much guidance in terms of total dose evaluation for all the common natural radionuclides present in water samples.

The approach used for radioactivity dose evaluation in this guideline builds on the total dose approach first developed for the Mooi River water radioactivity study, and serves to expand upon and clarify the uncertainties in assumptions met with in that study. The radioactivity dose is evaluated in terms of the five-colour classification approach well accepted for chemical and microbiological water quality in South Africa for classification of the water quality in the classes: Ideal (blue), good (green), marginal (amber), poor (red) and unacceptable (purple).

During the production of this document there was much discussion and controversy as to whether the department should adopt the life-time age weighted method of evaluating the significance of the radioactivity dose, or should rather be conservative and adopt the dose to the most sensitive user (usually infants under one year of age) for the purposes of classification.

The majority opinion has been adopted of using the lifetime age-weighted approach yet while also explicitly showing the dose values for all the specific age groups, should the user of the guideline wish to make either more or less conservative evaluations of water radioactivity in specific age group situations.

It is hoped that this guideline, with the associated computer software routine, should make it easier for hydrologists, and all those concerned with evaluation of radioactivity in water to assess the fitness for use of drinking water for radioactivity parameters.

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Department of Water Affairs & Forestry.
March 2002

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Glossary of Terms

Action Level	The level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic exposure or emergency exposure situations.
Alpha Radiation	This is emission of energy from the atomic nucleus as alpha particles. Alpha particles are comparatively large, positively charged nuclei of helium and have a low penetrating power, e.g. being stopped by a few centimetres of air or a sheet of paper.
Artificial radioactivity	Radioactivity not of a natural origin (see definition of NORM) and produced as a result of human technological processes, for example, inside a nuclear power reactor.
Background	The surrounding environment which is uncontaminated by a local source of pollution.
Background Radiation	The radiation in the natural environment, including cosmic and cosmogenic radiation and radiation from the naturally occurring radioactive elements. It is also called natural background radiation.
Beta Radiation	This is emission of energy from the atomic nucleus as beta particles. Beta particles are equivalent to electrons and are able to penetrate up to around a metre of air or a centimetre of water.
Bio-concentration	The process by which contaminants in the environment are concentrated up the food chain (e.g. from benthic organisms, to fish, to humans).
Cosmic radiation	Radiation of great penetrating power that come to the earth from all directions of space.
Cosmogenic radiation	Radiation that results from the interaction of cosmic radiation with the earth's atmosphere, for example radioactive carbon –14 is created in the earth's atmosphere.
Critical Group	A group of members of the public (in the general population) which is reasonably homogeneous with respect to its exposure for a given radiation source and given exposure pathway and is typical of individuals receiving the highest dose by the given exposure pathway from the given source.
Dose – Effective	A weighted measure of the radiation energy received or absorbed by the whole body and measured in units of Sievert (Sv)
Dose – Annual Effective, Age Specific	A weighted measure of the radiation energy received or absorbed by the whole body and measured in units of Sievert (Sv), following uptake of a certain amount of radioactivity in a year where the dose will be committed over the lifetime of the

	person taking into consideration the sensitivity of the human body at the age when the uptake occurred.
Dose – Annual Effective, Lifetime Average	A weighted measure of the average radiation energy received or absorbed by the whole body and measured in units of Sievert (Sv), assuming that uptake of a certain amount of radioactivity occurs in a year over the whole lifetime of a person and taking into consideration of the sensitivity the human body at different age intervals into consideration.
Dose Limit	The value of the effective dose to individuals from controlled practices or working activities that shall not be exceeded.
Dose rate	The amount of ionising radiation that may have been received over any period of time.
Exclusion	Any exposure where the magnitude or likelihood is essentially not amenable to control. Examples are exposure from Potasium-40 (K-40) in the body, from cosmic radiation at the surface of the earth and from unmodified concentrations of nuclides in most raw materials.
Exposure	The act or condition of being subject to ionising radiation.
Exposure Pathways	The routes by which radioactive material can reach or irradiate humans.
Gamma Radiation	High energy, short-wave length electromagnetic radiation of nuclear origin. Gamma rays are the most penetrating when compared to alpha and beta radiation.
Groundwater	Water beneath the earth□s surface, accumulating as a result of infiltration and seepage, and serving as the source of springs, wells, etc.
Intake	The process of taking nuclides into the body either by inhalation (typically as dust in air) or by ingestion (drinking water and/or eating food).
Intervention	Any action intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice or which are out of control as a consequence of an accident.
Intervention Level	The level of avertable dose at which a specific protective action or remedial action is taken in an emergency exposure situation or a chronic exposure situation. This may also include exposure to natural occurring radioactive material not caused by any human activity, i.e. extraordinary high background radioactivity.
NORM	Naturally Occurring Radioactive Material. The main contributions of human exposure to ionising radiation

arise from natural sources – cosmic rays, the nuclides in the earth's crust and the natural radioactivity of the human body. Of the natural nuclides in the earth's crust (NORM), those which are found to be the main sources of human radiation exposure are Potasium-40 (K-40), Thorium-232 (Th-232), Uranium-235 (U-235) and Uranium-238 (U-238) and decay products from the latter three nuclides.

Potassium is a common element and the radioactive isotope, K-40, constitutes 0.012% of all potassium in its natural form.

The three heavy nuclides (Th-232, U-235 and U-238) decay to produce other elements, which in turn decay further through a chain which includes several elements, eventually to end in stable isotopes of lead. An example of a significant daughter nuclide in these decay chains is Radium-226 (Ra-226 in the U-238 chain) and which is soluble in water.

Nuclide/Radionuclide	A radionuclide is an element or isotope that is radioactive as a result of the instability of the nucleus of its atom (e.g. radium or uranium). In this document all reference to nuclides will assume these to be radionuclides.
Nuclide vector	A specific set of nuclides that is used for analysis and/or evaluation of water quality, e.g. a simple water analysis with the purpose of only obtaining an initial indication of water quality may consist of the nuclide vector {U-238; Ra-226}. A more complex analysis to determine the radiation dose more precisely may consist of more nuclides in the U-238, U-235 and Th-232 decay chains.
Pathways Analysis	A method of estimating the transfer of contaminants (e.g. radio-nuclides released in water) and subsequently accumulated up the food chain to fish, vegetation, mammals and humans and the resulting radiological dose to humans.
Potential Exposure	Exposure that is not expected to be delivered with certainty but that may result from an accident at a source of radioactive material, or owing to an event or sequence of events of a probabilistic nature.
Practice	Any human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed. Some mining and mineral processing activities fall within this definition and are normally authorised and regulated in terms of the National Nuclear Regulator Act (Act No. 47 of 1999).
Radiation	The emission and propagation of energy through space or matter in the form of electromagnetic waves (gamma rays) or fast-moving particles such as alpha and beta particles.

Radioactive	The condition of a material exhibiting the spontaneous decay of an unstable atomic nucleus into one or more different elements (e.g. uranium decays into various isotopes of radium, thorium and lead).
Radioactive Waste	Material, whatever its physical form, remaining from practices or interventions and for which no further use is foreseen (i) that contains or is contaminated with radioactive substances and has an activity or activity concentration higher than the level for clearance or exemption from regulatory requirements, and (ii) to which exposure is not excluded from regulatory control.
Radon Gas	A naturally occurring radioactive gas within the decay chain of U-238.
Receptor	A person living nearby to a source of pollution; the person who may receive any impacts resulting from an industrial activity.
Reference Level	This can be an action level, intervention level, investigation level or recording level. Such levels may be established for any of the quantities determined in the practice of radiation protection.
Remedial Action	Action taken to reduce radiation doses that might otherwise be received.
Risk	A multi-attribute quantity expressing hazard, danger or chance of harmful or injurious consequences associated with actual or potential exposures. It relates to quantities such as the probability that specific deleterious consequences may arise and the magnitude and character of such consequences.
Source	Anything that may cause radiation exposure, such as by emitting ionising radiation or releasing radioactive substances or materials. For example, natural materials emitting radon are sources in the environment.

Symbols and Abbreviations

Ac	Actinium
Bi	Bismuth
Bq	becquerel
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
ILO	International Labour Organisation
mSv	10^{-3} sievert
NNR	National Nuclear Regulator
Pa	Protactinium
Pb	Lead

pico	10^{-12}
Po	Polonium
Ra	Radium
Rn	Radon
Sv	Sievert
Th	Thorium
U	Uranium

1. Purpose

The purpose of this document is to present a guideline for evaluating the quality of drinking water in respect of its radioactivity concentration. This document deals with naturally occurring radioactive material (NORM) in water. Artificial sources of radioactivity are outside the scope of this document although it is briefly discussed. Sediments that occur in natural water bodies, such as in river streams and that can trap NORM material, is also outside the scope of this document.

This document presents proposals for radioactivity monitoring and dose calculation methods that can be used to specify the quality of a water resource.

2. Introduction

The annual radiological dose for a person drinking water that contains a certain level of radioactivity is calculated by an apparently simple equation as follows:

Annual Effective Dose (Sv) = Radioactivity Concentration in water (Bq/L) × Annual Consumption of water (L) × Radioactivity Dose Conversion Factor (Sv/Bq)

However, it is far from simple to obtain input data for the variables in the equation that will allow one to assess the quality of a specific water resource and quantify the dose for people using the water. The Mooi River and Klip River studies [1] provided ample proof of the complexities involved in studies to determine radioactivity concentrations in water and the associated health risk.

The main source of radioactivity impact on water is naturally occurring radioactive material NORM. It is present in all water resources and the impact is normally of a chronic nature. The proposed methods for the guideline therefore deal with water that contains NORM.

Some readers of this document may be unfamiliar with the subject of radiological protection and for this reason the document has been structured in three sections as follows:

- A first section that gives a general introduction to radioactivity and protection against ionising radiation.
- The second section provides background to the specific situation of chronic exposure situations as well as supporting information for assumptions made in the proposed guideline.
- The third section describes the guideline for evaluating water quality.

The reader who is familiar with radioactivity and radiation health hazards is advised to start at Section 2 of the document.

SECTION 1

Radioactivity and Protection against Ionising Radiation

3. Radioactivity and ionising radiation [2]

3.1. Radiation in everyday life

Radioactivity is a part of our earth and has existed since the beginning of time. Naturally occurring radioactive material (NORM) occurs everywhere and is present in the earth's crust, the floors and walls of our homes, schools, or offices and in the food we eat and drink. There are radioactive gases in the air we breathe. Our own bodies (muscles, bones, and tissue) contain naturally occurring radioactive elements. Man has always been exposed to natural radiation arising from the earth as well as from outside the earth. The radiation we receive from outer space is called cosmic radiation or cosmic rays.

We also receive exposure from man-made radiation, such as X-rays, radiation used to diagnose diseases and for cancer therapy. Fallout from nuclear explosives testing, and small quantities of radioactive materials released to the environment from coal and nuclear power plants, are also sources of radiation exposure to man.

Radioactivity is the term used to describe the disintegration of atoms. The atom can be characterised by the number of protons in its nucleus. Some natural elements are unstable. Therefore, their nuclei disintegrate or decay, thus releasing energy in the form of radiation. This physical phenomenon is called radioactivity and the radioactive atoms are called radionuclides, or nuclides for short in this document. A unit of weight such as the gram is not useful to express radioactivity since 15 picograms of thorium-234, for example, is approximately equivalent in radioactivity to 1 gram of uranium-238. Radioactive decay is expressed in units called becquerels (Bq). One Bq equals one disintegration per second. Examples of radioactivity that can occur in some natural and artificial materials [3] are as follows:

Table 3.1: Examples of Radioactivity

Example of material	***Activity***	***Type of activity***
1 kg of granite	1000 Bq	NORM
1 kg of coffee	1000 Bq	NORM
1 kg of coal ash	2000 Bq	NORM
1 kg superphosphate fertiliser	5000 Bq	NORM
1 adult human	7000 Bq	NORM
1 household smoke detector	30 000 Bq	Artificial
1 kg low level radioactive waste	1 000 000 Bq	Artificial
Radioisotope source for medical therapy (Typically Cobalt-60)	100 000 000 000 000 Bq	Artificial

The nuclides decay at a characteristic rate that remains constant regardless of external influences, such as temperature or pressure. The time that it takes for half the nuclides to disintegrate or decay is called half-life. This differs for each nuclide, ranging from fractions of a second to billions of years. For example, the half-life of Iodine-131 is eight days, but for Uranium-238, which is present in varying amounts all over the world, it is 4.5 billion years. Potassium-40, the main source of radioactivity in our bodies, has a half-life of 1.42 billion years.

3.2. Types of radiation

The term "radiation" is very broad, and includes such things as light and radio waves. In our context it refers to "ionising" radiation, which means that because such radiation passes through matter, it can cause it to become electrically charged or ionised. In living tissues, the electrical ions produced by radiation can affect normal biological processes. There are various types of radiation, each having different characteristics. The common ionising radiations generally talked about are and that can be associated with water with elevated radioactivity levels, are:

- Alpha radiation: This consists of heavy, positively charged particles emitted by large atoms of elements such as uranium and radium. Alpha radiation can be stopped completely by a sheet of paper or by the thin surface layer of our skin (epidermis). However, if alpha-emitting materials are taken into the body by breathing, eating, or drinking, they can expose internal tissues directly and may, therefore, cause biological damage.

- Beta radiation: This consists of electrons. They are more penetrating than alpha particles and can pass through up to around 1 centimetre of water. In general, a sheet of aluminium a few millimetres thick will stop beta radiation.

- Gamma rays: This is electromagnetic radiation similar to X-rays, light, and radio waves. Gamma rays, depending on their energy, can pass right through the human body, but can be stopped by thick walls of concrete or lead.

- Neutrons: These are uncharged particles and do not produce ionisation directly. But, their interaction with the atoms of matter can give rise to alpha, beta, gamma, or X-rays that then produce ionisation.

3.3. Radiation dose

Sunlight feels warm because our body absorbs the infrared rays it contains. But, infrared rays do not produce ionisation in body tissue. In contrast, ionising radiation can impair the normal functioning of the cells or even kill them. The amount of energy necessary to cause significant biological effects through ionisation is so small that our bodies cannot feel this energy as in the case of infrared rays, which produce heat.

The biological effects of ionising radiation vary with the type and energy. A measure of the risk of biological harm is the dose of radiation that the tissues receive. The unit of absorbed radiation dose is the sievert (Sv). Since one sievert is a large quantity, radiation doses normally encountered are expressed in millisievert (mSv) or microsievert (μSv), which are one-thousandth and one-millionth of a sievert respectively. For example, one chest X-ray will give about 0.2 mSv of radiation dose. On average, our radiation exposure due to all natural background sources amounts to about 2.4 mSv a year, though this figure can vary, depending on the geographical location, by several hundred percent.

In homes and buildings, there are radioactive elements in the air. These radioactive elements are radon (Radon-222), thoron (Radon-220) and by-products formed by the decay of radium (Radium 226) and thorium present in many sorts of rocks, other building materials and in the soil. By far the largest source of natural radiation exposure comes from varying amounts of uranium and thorium in the soil around the world. The radiation exposure due to cosmic rays is very dependent on altitude, and slightly on latitude. People who travel by air, thereby, increase their exposure to radiation.

3.4. Radiation protection

It has long been recognised that large doses of ionising radiation can damage human tissues. Over the years, as more was learned about radiation, scientists became increasingly concerned about the potentially damaging effects of exposure to large doses of radiation. The need to regulate exposure to radiation prompted the formation of a number of expert bodies to consider what was needed to be done. In 1928, an independent non-governmental body of experts in the field, the International X-ray and Radium Protection Committee was established. It later was renamed the International Commission on Radiological Protection (ICRP). Its purpose is to establish basic principles for, and issue recommendations on, radiation protection. These principles and recommendations form the basis for national regulations governing the exposure of radiation workers and members of the public. They also have been incorporated by the International Atomic Energy Agency (IAEA) into its Basic Safety Standards for Radiation Protection published jointly with the World Health Organisation (WHO), International Labour Organisation (ILO), and the OECD Nuclear Energy Agency (NEA). These standards are used worldwide to ensure safety and radiation protection of radiation workers and the general public. It also forms the basis of the regulations in South Africa as applied by the National Nuclear Regulator to practices and working activities.

An intergovernmental body was formed in 1955 by the General Assembly of the United Nations as the UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). UNSCEAR is directed to assemble, study and disseminate information on observed levels of ionising radiation and radioactivity (natural and man-made) in the environment, and on the effects of such radiation on man and the environment.

Basic approaches to radiation protection are consistent all over the world. The ICRP recommends that any exposure above the natural background radiation should be kept as low as reasonably achievable, but below the individual dose limits. The individual dose limit for radiation workers averaged over 5 years is 100 mSv not exceeding 50 mSv in any one year, and for members of the general public it is 1 mSv per year. These dose limits have been established based on a prudent approach by assuming that there is no threshold dose below which there would be no effect. It means that any additional dose will cause a proportional increase in the chance of a health effect. This relationship has not yet been established in the low dose range where the dose limits have been set. Use of this relationship corresponds to a precautionary approach.

There are many high natural background radiation areas around the world where the annual radiation dose received by members of the general public is even higher than the ICRP dose limit for radiation workers. The numbers of people exposed are too small to expect detectable increases in health effects epidemiologically. Still the fact that there is no evidence so far of any increase does not mean the risk is being totally disregarded. The ICRP and the IAEA recommend the individual dose must be kept as low as reasonably achievable, and consideration must be given to the presence of other sources that may cause simultaneous radiation exposure to the same group of the public. Also, allowance for future sources or practices just be kept in mind so that the total dose received by an individual member of the public does not exceed the dose limit.

3.5. At what level is radiation harmful?

The effects of radiation at high doses and dose rates are reasonably well documented. A very large dose delivered to the whole body over a short time will result in the death of the exposed person within days. Much has been learned by studying the health records of the survivors of the bombing of Hiroshima and Nagasaki. We know from these that some of the health effects of exposure to radiation do not appear unless a certain quite large dose is absorbed. However, many other effects, especially cancers are readily detectable and occur more often in those with moderate doses. At lower doses and dose rates, there is a degree of recovery in cells and in tissues. However, at low doses of radiation, there is still considerable uncertainty about the overall effects. It is presumed that exposure to radiation, even at the levels of natural background, may involve some additional risk of cancer. However, this has yet to be established. To determine precisely the risk at low doses by epidemiology would mean observing millions of people at higher and lower dose levels. Such an analysis would be complicated by the absence of a control group that had not been exposed to any radiation. In addition, there are thousands of substances in our everyday life besides radiation that can also cause cancer, including tobacco smoke, ultraviolet light, asbestos, some chemical dyes, fungal toxins in food, viruses, and even heat. Only in exceptional cases is it possible to identify conclusively the cause of a particular cancer. There is also experimental evidence from animal studies that exposure to radiation can cause genetic effects. However, the studies of the survivors of Hiroshima and Nagasaki give no indication of this for humans. Again, if there were any hereditary effects of exposure to low-level radiation, they could be detected only by careful analysis of a large volume of statistical data. Moreover, they would have to be distinguished from those of a number of other agents which might also cause genetic disorders, but whose effect may not be recognised until the damage has been done (thalidomide, once prescribed for pregnant women as a tranquilliser, is one example). It is likely that the resolution of the scientific debate will not come via epidemiology but from an understanding of the mechanisms through molecular biology. With all the knowledge so far collected on effects of radiation, there is still no definite conclusion as to whether exposure due to natural background carries a health risk, even though it has been demonstrated for exposure at a level several times higher.

The following gives an indication of the possible effects and implications of a range of radiation doses and dose rates to the whole body, as well as examples of low levels of chronic (or chronic) exposure situations:

Table 3.2: Description and Effects of Different Doses and Dose Rates

Dose	***Description / Effects***
0.3 to 0.6 mSv/a	This is the typical range of dose rates from artificial sources of radiation, mostly medical.
0.2 to 0.8 mSv/a	This is the range of worldwide average annual radiation dose from ingestion of foodstuff and water. Variations about the mean values by factors 5 to 10 are not unusual for many components of exposure from natural sources.
2.4 mSv/a (approximately)	The normal average background radiation from natural sources. Approximately half of this exposure is from radon in air.
13 mSv/a	This is the highest known average annual dose from

Dose	Description / Effects
	background radiation that occurs in the Kerala and Madras states in India where a population of over 100 000 people is exposed to this level.
20 mSv/a	This dose averaged over 5 years is the limit for regulated practices and working activities such as the nuclear industry employees and mining and mineral processing workers, who are closely monitored.
50 mSv/a	This dose is conservatively the lowest dose rate where there is any evidence of cancer being caused. It is also the dose rate that arises from natural background levels in several places. Above this, the probability of cancer occurrence (rather than the severity) increases with dose.
1000 mSv	This dose accumulated over some time, would probably cause a fatal cancer many years later in 5 of every 100 persons exposed to it (i.e. if the normal incidence of fatal cancer were 25%, this dose would increase it to 30%).
1 000 mSv	This dose received as a short-term dose would probably cause (temporary) illness such as nausea and decreased white blood cell count, but not death. Above this dose the severity of illness increases with dose.
Between 2 000 and 10 000 mSv	This dose over a short-term dose would cause severe radiation sickness with increasing likelihood that this would be fatal.
10 000 mSv	This dose in a short-term dose would cause immediate illness and subsequent death within a few weeks.

3.6. Risks and benefits

We all face risks in everyday life. It is impossible to eliminate them all, but it is possible to reduce them. The use of coal, oil, and nuclear energy for electricity production, for example, is associated with some level of risk to health, however small. In general, society accepts the associated risk in order to derive the relevant benefits. Any individual exposed to carcinogenic pollutants will carry some risk of getting cancer. The use of radiation and nuclear techniques in medicine, industry, agriculture, energy and other scientific and technological fields has brought significant benefits to society. The benefits include medicine for diagnosis and treatment of certain kinds of cancer.

Strenuous attempts are made in the nuclear industry to reduce risks to as low as reasonably achievable. The scientific field of radiation protection sets examples for other safety disciplines in two unique respects:

- Firstly, there is the assumption that any increased level of radiation above natural background will carry some risk of harm to health.
- Secondly, it aims to protect future generations from activities conducted today.

3.7. Artificial radioactivity

A brief discussion is included at this point on artificial radioactivity originating at nuclear facilities such as nuclear power stations, for example. There are very few nuclear facilities in South Africa when compared to other countries such as in Europe. Potentially significant impacts from these facilities usually only occur during abnormal operating or accident conditions.

Monitoring of the potential impact on water from practices such as nuclear power stations, is normally covered by extensive monitoring programmes implemented by the practice and the NNR, as is prescribed by the operating licence conditions issued in terms of the National Nuclear Regulator Act (Act No. 47 of 1999). These programmes include monitoring procedures for specific nuclides typical of the nuclear fission process. The nuclides are mostly short-lived beta particle emitters compared to typical NORM nuclides that also include alpha particle emitters. Annual Allowable Discharge Quantities (AADQ's) are established for each nuclear facility. The AADQ's are related to the nuclide spectrum of routine releases from the facility and the annual dose constraint for the facility (typically 250 μSv/a).

SECTION 2

Chronic Exposure Situations and Supporting Information for Assumptions made in the Proposed Guideline

4. Chronic and persistent exposure situations

An example of chronic exposure from natural sources is that of cosmic radiation. People living at high altitudes receive more cosmic radiation than a person living at sea level. An inhabitant of La Paz, Bolivia, receives approximately 6 times more cosmic radiation than a person living at sea level. Cosmic radiation is an example of chronic exposure that is essentially uncontrollable or not amenable to control. It is generally excluded from the scope of regulations on radiological protection.

There is no water resource that does not contain NORM. The potential health risk associated with drinking water will therefore mainly be the result of chronic exposure to elevated levels of dissolved NORM, because of the ubiquitous nature of NORM. An example of such a situation is that of a community dependent on a water resource that has higher than typical concentration levels of natural occurring nuclides. Some borehole water in the Namakwa Land region, for example, exhibits Ra-226 concentration levels in excess of 1 Bq/L. The potential annual dose to an adult as a result of Ra-226 alone in such a situation is more than 0.2 mSv. This is double the WHO recommended value of a 0.1 mSv/a [5]. (It is important to note that WHO also recommends that this value should be adapted to local conditions; increased or decreased depending on the site-specific conditions.)

When one assesses chronic exposure situations, the relevant quantity is the annual effective dose attributable to the exposure. The dose as a result of chronic exposure from natural sources is termed the ***existing annual dose***. The example of water with a high natural concentration of radium is that of an existing annual dose for people drinking that water. If a working activity, for example a mine, adds to the existing annual dose, the added component is termed the ***additional annual dose***. The additional annual dose is therefore the result of human activities and is additional to the background dose that would have existed prior to human activities.

Members of the public may claim different levels of radiological protection depending on the source of exposure. The claim for protection is generally stronger when the source of exposure is a technological by-product rather than when it is considered to be of natural origin. Mining and mineral processes that can potentially (or actually) increase radioactivity in water bodies are subject to regulatory control in order to limit the additional annual dose to the public. Comparatively higher doses from purely natural radiation that is part of the existing dose (no contribution from practices or working activities) can be permitted.

5. Intervention

Radioactive residues already existing in some habitats, for example historic mine tailings and that could influence the radioactivity in water resources, can be subject to protective actions through a process called intervention, which is intended to lower the overall exposure to people.
The justification of intervention in chronic exposure situations should be assessed by means of a decision-aiding process requiring a positive balance of all relevant long-term attributes related to radiological protection. Attributes include:

- avertable annual dose that can be achieved through intervention, for example, water treatment that removes the radium from borehole water,
- expected reduction in anxiety caused by a situation of chronic exposure,
- the reassurance provided by the intervention,

- the social cost, harm and disruption that may be caused by the implementation of the intervention actions, and
- other considerations by relevant stakeholders.

The ICRP [4] refers to generic reference dose levels for intervention expressed in terms of the existing annual dose. These are useful in some situations such as exposures to high natural background radiation and radioactive residues that are a legacy from the distant past. Generic reference levels, however, should not prevent protective actions at lower dose levels to reduce the contribution from dominant exposure components when it is justifiable. According to the ICRP an existing annual dose approaching 10 mSv may be used as a generic reference level below which intervention is not likely to be justifiable for some chronic exposure situations. Below this level, protective actions to reduce the dominant component to the existing annual dose are still optional and might be justifiable. If, for example, cosmic radiation is the dominant component to a natural background radiation dose of 10 mSv/a, intervention may not be justifiable. However, if water is the dominant component for a large population group for a specific situation where elevated NORM as a result of the peculiar geology of the area, impacts on the water resource, intervention may be justifiable.

An ***intervention exemption level*** equal to 1 mSv has been proposed in the ICRP report. Natural sources of water with a high concentration should be regarded as falling in the same category of cases where an exemption level could apply.

Table 5.1 presents a summary of dose concepts in relation to intervention [4].

Table 5.1: Guideline for Decisions on Intervention For Different Levels of Annual Doses

Dose Description	***Dose Value***	***Concept***
Existing annual dose (including background dose): Chronic annual dose attributable to all sources at a given location that result in the various exposure pathways.	~100 mSv/a	Generic dose reference level where interventions is almost always justifiable. Above this level intervention should be considered almost always justifiable.
	~10 mSv/a	Generic dose reference level for interventions not likely to be justifiable. Below this level intervention is optional but not likely to be justifiable and above this level intervention may be necessary.
Existing annual dose as a result of a specific source of the natural background radiation, e.g. a water resource, radon, etc.	~1 mSv/a	Below this level intervention is not justifiable.
Additional annual dose, above background, as a result of current practices and working activities.	~1 mSv/a	Public dose <u>limit</u> for practices.
Additional annual dose, above background radiation, attributable to a practice or working activity.	0.3 mSv/a ≤ dose ≤ 1 mSv/a	Internationally proposed dose <u>constraint</u> for practices and working practices.

6. Behaviour of naturally occurring nuclides in the environment

6.1. Introduction

The magnitude of dose from ingesting water is to a large extent determined by those nuclides that have high dose coefficients and remain in solution. The sections that follow are extracts from an article on the typical geo- and hydrochemical behaviour of important NORM nuclides [6]. This information forms part of the basis for a screening assessment in the proposed guideline methodology.

6.2. Uranium and thorium nuclides

Important primordial nuclides in nature are the long-lived nuclides thorium-232 (Th-232), uranium-235 (U-235) and uranium-238 (U-238) as well as potassium-40 (Ka-40). Thorium and uranium are concentrated in crustal rocks in an average Th:U ratio of about 3.5. However, the various igneous, metamorphic and sedimentary rock types have widely different U and Th concentrations. Some metamorphic rocks, for example, have a high abundance of U and Th. U is also found to be strongly enriched in certain organic sediments e.g. peat, lignite and asphalt.

In a closed system the progeny of Th and U are present in concentrations determined by the concentration of parent U and Th isotopes and the time since the system became closed to nuclide migration. In nature closed systems rarely exist and predictions regarding nuclide concentrations in water bodies invariably include large uncertainties. These nuclides and their decay products are found in ground and spring waters in element specific concentrations dependent on complex hydrogeologic processes and conditions (dissolution, transport and ion-exchange processes as well as redox potentials and pH-conditions of the aqueous system). These hydrogeologic processes result in non-equilibrium conditions between parent nuclides and their progeny. However, characteristic behaviour in the natural environment can provide a basis for assumptions regarding probable behaviour of nuclides used in the radioactivity screening assessment methodology in the proposed guideline. This characteristic behaviour is briefly discussed.

In the oxidised zone of the earth's near-surface environment Th and U may both be mobilised, but in different ways. Thorium has an extremely low solubility in natural waters. There is a close correlation of Th concentration and detrital content of water. Th is almost entirely transported in particulate matter. Th is bound in insoluble resistate minerals or is adsorbed on the surface of clay minerals. Even when Th (e.g.Th-230) is generated in solution by radioactive decay of U-234 it rapidly hydrolyses and adsorbs on to the nearest solid surface. The soluble Th content of water was shown to be insignificant during the Klip and Mooi Rivers catchment radioactivity studies [1]. (However, sediments can transport NORM some distance from the point of origin.)

By contrast, U may either move in a detrital, resistate phase, similar to Th, or in solution as a complex ion. Both elements appear in the 4^+ oxidation state in primary igneous rocks and minerals, but U, unlike Th, can be oxidised to 5^+ and 6^+ states in the near-surface environment. The 6^+ oxidation state forms soluble uranyl complex ions which play the most important role in U transport during weathering.

Waters in the natural environment are variable in U content, depending mainly on factors such as contact time with U-bearing rock, U content of the contact rock, amount of evaporation and availability of complexing ions. Groundwaters are somewhat enriched in respect of U when compared to surface waters especially in mineralised areas.

The ability of U to undergo inorganic dissolution and reprecipitation is probably the most important process in the natural environment to cause disequilibrium between the nuclides in the decay chains. Large variations of U can sometimes be observed in the same aquifer and are interpreted as due to Eh-pH changes which cause precipitation of U from solution along the flow direction.

6.3. Other NORM nuclides

Disequilibrium between U-238 and U-234 in natural waters has been found to be the rule rather than the exception, for example, preferential leaching from radiation damaged sites in crystalline material, following decay down to U-234. At relatively high concentrations of U, the Klip and Mooi Rivers studies indicate that disequilibrium is not pronounced and that equilibrium conditions can be assumed in a screening survey.

Radium-226 (Ra-226), the daughter of Th-230, is generally found in excess of its parent in most natural waters due to the greater solubility of Ra over Th. In freshwaters, radium is found in highest concentrations in limestone regions where it is more soluble in HCO_3- waters. Ra-228 is also found in excess of its parent Th-232 in natural waters.

Products of radioactive decay in the U and Th series include radon (Rn) gas of which three isotopes exist. Rn-222 is the longest-lived and most abundant. Loss of radon will cause disequilibrium between members of a decay chain. Rn-222 has an appreciable solubility in water (about 0.5 g/L at STP) and is often found in concentrations far in excess of the parent nuclide radium, Ra-226 (so-called unsupported Rn-222). A Rn-222/Ra-226 activity ratio of 450 has been observed in groundwaters from central England [14]. Aeration of water and short half-lives make the contribution of radon negligible in ingestion dose calculations. Normally radon is only considered for confined areas, e.g. showers using radon rich natural water and when inhaling the radon progeny are the exposure pathway. This is considered a negligible exposure pathway since showers are usually supplied with treated water from which any dissolved radon would have been released during the treatment process.

Polonium-210 (Po-210) is largely insoluble. In the hydrological cycle Po-210 generally follows its precursor Lead-210 (Pb-210). Po-210 is generally more readily adsorbed than Pb-210 onto particulate matter.

The decay product Protactinium-231 (Pa-231 from U-235) is relatively insoluble when compared to uranium and radium, for example.

7. Typical water quality criteria

7.1. Criteria

Criteria that are generally used for drinking water quality assessments can be expressed in terms of any of the following quantities:

- Dose
- Activity concentration

- Chemical concentration
- Qualitative health risk e.g. stated as increased morbidity or cancer risk
- Quantitative health risk e.g. fatality risk per year

A quantitative health risk for exposure to radioactivity can be estimated by using a nominal value of 5% per Sievert. This value is for mortality from cancer after exposure to low doses for a population of all ages and as recommended by the ICRP [7]. Inclusion in the water quality guideline of a quantitative risk criterion expressed as a statistical mortality risk is, however, not recommended. The public generally finds it confusing when risk is expressed in statistical terms. Factors, for example, that result in increased public concern in health risk matters include the following [8]:

- Unfamiliarity with a certain type of risk
- Mechanisms or process of how a risk arises are not understood
- Risk is scientifically uncertain and expressed in statistical terms
- Delayed effects are part of the risk, for example when a health effect only manifest itself some time after exposure to a hazardous material

These factors are all elements of ionising radiation health risks. Communication with the general public on water quality in terms of radioactivity and radiation hazards, should preferably not include unfamiliar terms such as sieverts, becquerels and statistical fatality risk. However, the method of communication must still allow a clear grasp of the radiation health hazard associated with a specific source of water.

The American Health Physics Society also recommends against quantitative estimation of radiation health risk below an individual dose of 50 mSv per year, additional to background radiation. The reason given is that there exists no conclusive evidence of health risks for low dose rate annual doses up to 50 mSv [9]. Statistically significant risks for solid tumors in the LSS cohort (Life Span Study cohort of the Japanese A-bomb survivors) are presently seen only above a dose of 100 mSv (short-term low-energy transfer doses).

7.2. Guideline examples

It is essential that when preparing a guideline, other international guidelines be considered, especially for those countries with which important trade links exist, for example the United States and the European Community.

The criteria used by the USA and the European Union are compared in the table that follows.

Table 7.1 US and EU Guidelines [10;11]

Regulatory Authority	*Chemical concentration*	*Activity concentration*	*Radiation dose*	*Quantitative health risk*	*Qualitative health risk*	*Comments*

US EPA	Uranium: 30 µg/L	Alpha particles: 555 mBq/L Combined Ra-226 and Ra-228: 185 mBq/L	Beta particles and photon emitters: 0.040 mSv/a	–	Levels stated for MCL (Maximum Contaminant Level), the highest level of a contaminant that is allowed in drinking water	Standards apply to public water distribution networks.
European Union	–	–	0.100 mSv/a	–	–	Radiation dose is the indicator parameter for water intended for human consumption.

The German Commission for radiation protection, "Strahlenschutz-Kommission" (SSK), gave some recommendations on the basis of practicability to evaluate natural radioactivity in water [12]. The relative mobility of the ions of the primordial nuclides in water is stated to be in the order $U^{6+} > U^{4+} >> Th^{4+}$. As a consequence of these different mobilities the Th-isotopes are ignored as constituents of aqueous systems. The same is mostly true for their radium progeny. Ra-226 as progeny of U-238 is more relevant than Ra-228 in the Th-232 decay chain.

The SSK has also recommended an additional annual dose of 0.500 mSv as limit from tap water where water resources are affected by former uranium mining activities.

The SSK further defines relevant natural nuclides in tap water to be U-238, U-234, Ra-226, Rn-222, Pb-210 and Po-210. No Th-232 and U-235 progeny is included.

In South Africa domestic water refers to all uses to which water can be put in the domestic environment (drinking, food preparation, bathing, washing dishes, laundry and gardening). The EU uses the concept of “water intended for human consumption” and is defined as follows [13]:

“- all water either in its original state or after treatment, intended for drinking, cooking, food preparation or other domestic purposes, regardless of its origin and whether it is supplied from a distribution network, from a tanker, or in bottles or containers;
- all water used in any food-production undertaking for the manufacture, processing, preservation or marketing of products or substances intended for human consumption unless the competent national authorities are satisfied that the quality of the water cannot affect the wholeness of the foodstuff in its finished form.”

The EU Directive also states that the directive does not apply, or a member state is exempt, when “water intended for human consumption from an individual supply providing less than 10 m^3 a day as an average or serving fewer than 50 persons, unless the water is supplied as part of a commercial or public activity.”

The EU Directive value of 0.100 mSv/a is described as an indicator parameter and the value has been selected to ensure that water intended for human consumption can be consumed safely on a lifelong basis. The same value of 0.100 mSv/a is described by WHO as a screening value [5].

7.3. UNSCEAR data on radioactivity in drinking water [14]

UNSCEAR provides information on nuclides in drinking water for different regions and countries in the world. The information in Table 7.1 indicates that most countries report U-238 and/or Ra-226. It is deduced that mostly these two nuclides are used for purposes of screening water for its radioactivity content.

The wide ranges that are reported for some countries stem from the fact that the data reflect all kinds of water sources, e.g. ground water, lakes and treated water.

Table 7.2 International Drinking Water Radioactivity Concentrations; mBq/L

(Note: Empty cells in the table indicate that no values are reported.)

Country	***U-238***		***Th-230***		***Ra-226***		***Pb-210***		***Po-210***		***Th-232***		***Ra-228***		***Th-228***		***U-235***	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
U.S.A.	0.3	77	0.1		0.4	1.8	0.1	1.5			0.05		0	0.05			0.04	
China	0.1	700			0.2	120					0.04	12						
India	0.09	1.5																
Finland	0.5	150000			10	49000	0.2	21000	0.2	7600			18	570				
France	4.4	930			7	700					0	4.2						
Germany	0.4	600			1	1800	0.1	200	0.1	200								
Italy	0.5	130			0.2	1200												
Poland	7.3		1.4		1.7	4.5	1.6		0.5		0.06							
Romania	0.4	37			0.7	21	7	44	7	44	0.04	9.3						
Switzerland	0	1000			0	1500							0	200			0	50
Spain	3.7	4.4			20	4000												
U.K.					0	180	40	200										

Remark: The wide range in water activities for some EU countries, e.g. Finland, and some low minimum values should be noted.

8. Water treatment and its effect on NORM concentrations

Water treatment processes that are part of large water distribution networks, for example in towns and cities, cause a significant decrease in NORM when compared to the concentrations in the raw feedwater. These processes include aeration, flocculation, sedimentation, pH-adaption and filtration. It is therefore only necessary to perform comprehensive nuclide analysis in the initial phase of monitoring. But once typical nuclide concentrations have been established, it could be justified that routine monitoring comprise of only a few indicator nuclides.

Another process that efficiently removes heavy metals and therefore also uranium, lead, polonium and radium, is flocculation. The nuclides are co-precipitated with other unwanted constituents and most of the radioactivity reports to the sludge that is generated by water treatment facilities

9. Uncertainty

Uncertainty is introduced into any dose calculation through many different factors. Examples are:

- Water consumption rates for different age groups and different individuals and which reflect the heterogeneity in a population. Using a default consumption figure of 730 L (adults) for a specific water source, especially if it is a category A or B water source as defined in Section 13, is probably too conservative.
- An individual generally uses different water sources during his/her lifetime.
- Sampling strategies and techniques introduce uncertainty dependent on temporal and other variations in a catchment area or water resource.
- Dosimetric models are subject to scientific uncertainty. There are important gaps in current understanding of the typical biological behavior of many nuclides.
- Cancers induced by radiation are similar to those that are caused by many other agents. The effects can therefore only be demonstrated as a statistical excess of cancers in the exposed population, i.e. through epidemiological studies. Epidemiological studies of low-level radiation effects are complicated by the need for a large sample. For example, to detect a relative risk of 1.1 requires 2.36 million person-years for both the exposed and the control groups [15]. It is acknowledged that there are substantial uncertainties associated with interpretation of available epidemiological data for radiogenic cancer and extrapolation of that data to different populations and other radiation types, regardless of the assumption to extrapolate from high to low dose and dose rate [16].
- Even diurnal variations in atmospheric CO_2 seem to have an effect via pH changes on the activity concentrations of U nuclides in some surface waters [17].

Assessments of health effects of pollutants generally use models in which exposure variables and model parameters are point values, often chosen as conservative estimates. A more realistic approach is to characterise the uncertainty of each variable and parameter explicitly as a probability distribution. Quantification of uncertainty should be an integral part of the estimation of annual doses, especially where high doses may exist [4].

SECTION 3

A Guideline for Evaluating Drinking Water in terms of Naturally Occurring Radioactivity

10. Describing water quality in terms of its radioactivity content

The quality of water is described in terms of five water quality classes, each uniquely characterized by a colour. These water quality classes represent ranges of annual dose for daily use of a specific water source, associated health effects and typical exposure scenarios. Table 10.1 on the next page describes the different ranges of water quality.

The dose calculation method described in Appendix 1 estimate the annual dose for various age groups as well as the lifetime average annual dose. The following approach is followed for determining water quality:

1. Calculate dose to individual age groups.
2. If the difference between the minimum and maximum of these doses is less than a factor of five, calculate the weighted life-time average dose and use it for classification purposes.
3. If the difference between the minimum and maximum of these doses is more than a factor of five, use the maximum age specific dose for initial classification purposes.

No dose calculation method is presented for the rare event that artificial nuclides are detected in a water resource. In these cases special collaboration is required between DWAF, the NNR and the management of the practice that is the origin of these nuclides.

11. Water analysis and calculating the annual dose, D

11.1. Introduction

The extent of nuclide analysis of water should be a function of the following factors:

- The origin of the water
- The potential impacts by mining and mineral processes
- The scale of water use

These factors serve as basis for defining three categories of water sources that are defined and discussed in the section that follows.

11.2. Methods for determining annual dose estimates

11.2.1. Introduction

The assumed initial conditions for a water resource that requires evaluation are as follows:

- No prior radioactivity information exists.
- The person who has to evaluate the quality of the water is in a situation where he/she has to obtain an initial indication of water quality using a single or only a few samples.

Table 10.1: Different Ranges of Water Quality

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

There is normally no statistical dose correlation for uranium chemical concentration and gross alpha concentration, as is the case for the Klip river and Mooi river studies. It can be deduced from these studies that each water body or catchment area will have its own unique correlation between dose and uranium chemical concentration. This relation can only be established after many samples over a period of time. It was also shown that gross alpha activity concentrations could not be accurately correlated with dose.

The method for assessing water quality must avoid giving overly conservative results that could create wrong initial perceptions regarding the water quality. These perceptions are usually difficult to change afterwards. However, it is still required to have the precautionary principle included in the water quality assessment method so that the probability is low for underestimating dose in situations of elevated NORM concentrations.

Two different methods, as well as a combination of the two methods, are used, to determine the annual dose, D, (described in section 13.2.2 and 13.2.3) for the following three categories of water:

- Category A water use:

It is untreated water from a natural source (e.g. directly from a borehole, canal, river/stream or dam) with a low probability of being influenced by a mining and mineral processing activity.

- Category B water use:

It is untreated water from any source with a significant probability of being influenced by a mining and mineral processing activity e.g. a surface stream or borehole inside the potential impact radius of a mining and mineral processing facility.

- Category C water use:

It is treated water from a formal water source (e.g. water service providers such as Rand Water Board or a municipal waterworks) providing drinking water to a large number of people.

11.2.2. Calculation Method 1: A screening method

The screening method is designed to optimise costs without compromising the precautionary principle, when water may result in a high dose.

A two-nuclide *measurement* vector is required to perform an initial screening dose assessment, i.e. U-238 and Ra-226. Gross alpha specific activity and uranium chemical concentration do not allow a dose assessment of the required accuracy in the beginning. However, these two parameters are also measured and are used to check the validity of analysing only for U-238 and Ra-226. Low-probability nuclide behaviour, for example, a high relative abundance of Th isotopes, should be indicated by a low U concentration (ug/L) and a high gross alpha-activity concentration. This would then indicate a requirement for a detailed radioanalysis.

The dose is estimated using a six-nuclide *calculation* vector consisting of the following nuclides and assumptions:

U-234 in equilibrium with U-238

Pb-210 and Po-210 in equilibrium with Ra-226
U-235 = U238 ÷ 21.7

Note: U-235 was included since it has a fairly constant natural abundance in relation to U-238. Some laboratories provide U-235 along with U-238 and the measured value can then be used.

The screening method, which is intended for category A water, has relatively poor accuracy at very low radioactivity concentrations (dose in the range 0.01 mSv/a to 0.10 mSv/a) when compared to a calculation using a nuclide vector consisting of all measurable nuclides in the U-238, U235 and Th-232 decay chains. However, the assumption of Pb-210 and Po-210 in equilibrium with Ra-226, introduces adequate conservatism to flag a situation when the overall radioactivity concentration in the water increases and a typical constraint dose value 0.30 mSv/a is approached. At higher radioactivity concentrations the dose has a high probability of not being underestimated because of the conservative assumption regarding Po-210 and Pb-210.

The age group specific and lifetime average annual dose associated with a water resource is calculated as described in Appendix 1.

11.2.3. Method 2: A detailed method

Water sources used by a large number of people would require a larger nuclide *measurement* vector initially; due to collective dose considerations. As soon as acceptable correlation can be demonstrated between Method 2 and the Method 1 screening dose assessment, say after a year's monitoring, Method 1 can be used on a routine basis.

Method 2 is similar to Method 1 except that larger measurement and calculation vectors are used, as indicated in Table 13.1. Nuclides that are measured appear in bold letters. Unmeasured short-lived progeny are assumed to be in equilibrium with their parent nuclide except for the following nuclides:

- Ra-228 is assumed to be in equilibrium with Th-232.
- Ac-227 and Pa-231 are assumed to be in equilibrium with U-235.

Table 11.1 Method 2 Nuclide Calculation Vector

Nuclide
U-238
Th-234
Pa-234m
U-234
Th-230
Ra-226
Pb-210
Bi-210

Nuclide
Po-210
Th-232
Ra-228
Ac-228
Th-228
Ra-224
U-235
Th-231
Pa-231
Ac-227
Th-227
Ra-223

11.2.4. Comments on monitoring frequency and water analysis methods

Samples should be taken so that they are representative of the quality of the water consumed throughout the year.

The initial monitoring frequency should be quarterly, except where extraordinary nuclide concentrations exist (e.g. D > mSv/a) and more frequent monitoring is justified.

Sampling should preferably coincide with the monitoring programmes for other water contaminants. A comparative risk assessment of the pollutants in a water resource is essential in order to set priorities for water treatment. Radioactivity is only one of many agents that can cause adverse health effects, and in many cases in South Africa, it is secondary to some biological pollutants occurring in water that is used by informal settlements.

11.2.5. Framework for nuclide analysis and decision making

A framework for radioanalyses and water annual dose calculation is presented in Table 11.2.

Table 11.2 Analysis and Decision Making Guide

Category of water source	***Initial Analysis Method / Analyses***	***Nuclides in dose calculation and equilibrium assumptions***	***Annual Dose, D***	***Further actions***	***Routine Monitoring / Comments***
A Untreated water from a natural source not influenced by mining and mineral processing	Method 1 – Screening method • U-238 • Ra-226 • Gross alpha specific activity • U chemical concentration	• U-238 – U-234 • Ra-226 – Pb-210 – Po-210 • U-235 = U-238 ÷ 21.7	D < 1 mSv/a	• No further action required except to inform water users. • Whenever gross alpha > (2× U-238 + 3× Ra-226) then recommend a Method 2 analysis to determine the dose more accurately.	• Annual monitoring
			D > 1 mSv/a	• Perform water evaluation using Method 2 • If D ≤ 1 mSv/a following Method 2 analysis then no further action except to re-inform users and perform routine confirmatory monitoring. • If D > 1 mSv/a when using Method 2, intervention considerations are required.	• 3- monthly monitoring
B Untreated water from an informal source potentially influenced by mining and mineral processing	Method 1 – Screening method • U-238 • Ra-226 • Gross alpha specific activity • U chemical concentration	• U-238 – U-234 • Ra-226 – Pb-210 – Po-210 • U-235 = U-238 ÷ 21.7	D < 0.3 mSv/a	• No further action if total exposure from all exposure pathways to the critical group D ≤ 0.30 mSv/a; if not, perform Method 2 analysis to determine the dose accurately.	• 3- monthly monitoring • Liaison between NNR and DWAF required. Consult the impact assessment of the authorised activity.
			0.3 mSv/a < D < 1 mSv/a	• Re-assess dose by using Method 2. • No further action if total exposure to the critical group D ≤ 1 mSv/a and an optimised constraint cannot be achieved at less than 1 mSv/a	
			D > 1 mSv/a	• Confirm dose by using Method 2. • Intervention options to be evaluated (if mining and mineral processing is responsible for elevated radioactivity levels then definite remedial actions required)	• 3- monthly monitoring. • Liaison between DWAF and NNR required.
C Treated water delivered by a formal water distribution network (towns/cities)	Method 2: • U-238, Ra-226, Th-230, Pb-210, Po-210, Th-232, Ra-228, Th-228, Ra-224, Ra-223, Pa-231, Ac-227 • Gross alpha specific activity; • U chemical concentration	U-238 – Th-234 – Pa-234m – U234 U-235 = U-238 ÷ 21.7	D ≤ 0.1 mSv/a	• No further action	• 3 - monthly monitoring during first year. • For routine monitoring after first year use Method 1. • There is a high probability that the water source will meet recommended dose value of D = 0.10 when it is subjected to typical water treatment processes. • WHO guideline: provisional level of 2 ug/l uranium in drinking water.
			D > 01 mSv/a	• No further action if D ≤ 1 mSv/a and cost effective lowering of the dose cannot be achieved; if D > 1 mSv/a then special investigations required to lower dose to ≤ 1 mSv/a.	

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Appendix 1

Dose Calculation Methods

CALCULATION OF THE ANNUAL RADIATION DOSE

Introduction

Water resources that are either category A or C are usually evaluated by calculating the lifetime average annual dose. This calculation method is explained in the following section.

In some cases it may be necessary to evaluate a water resource by considering the most sensitive age group. This is the age group for which the lifetime dose committed during a specific year is the highest. The following approach is followed for determining water quality:

- Calculate dose to individual age groups.
- If the difference between the minimum and maximum of these doses is less than a factor of five, calculate the weighted life-time average dose and use it for classification purposes.
- If the difference between the minimum and maximum of these doses is more than a factor of five, use the maximum dose age specific dose for initial classification purposes.

The dose calculation methods are illustrated in the tables that follow.

Lifetime average annual dose [1]

The lifetime average annual dose associated with a water resource is 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 activity concentration of nuclide *i* (Bq/L)

F_i is a proportionality constant for nuclide *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.

Determination of Proportionality Constant F_i

The proportionality constant F_i for nuclide *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 an age group *x* (L/a)

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

W_x is a weighting factor for age group *x*

Table A1 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 nuclides and age groups were taken from the IAEA Basic Safety Standards [18].

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 lifetime average annual dose using Method 1 – a screening method

Table A2 illustrates the calculation of dose.

A default activity concentration equal to 1 Bq/L has been inserted for the analysed nuclides in the tables with the exception U-235 that is equal to U-238 divided by 21.7. The actual activity values for a water resource have to be determined through radioanalyses and equilibrium assumptions as described for Method 1 in the main text. The dose elements reported in the last column are therefore meaningless until real values are inserted.

Table A2: Lifetime Average Dose Calculation using Method 1 Analysis

Age Group	*Nuclide*	*Dcf; Sv/Bq*	*Activity; Bq/L*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
0-1yrs	U-238	3.4E-07	1.0E+00	2.0E+02	1.4E-02	9.5E-07
	U-234	3.7E-07	1.0E+00	2.0E+02	1.4E-02	1.0E-06
	Ra-226	4.7E-06	1.0E+00	2.0E+02	1.4E-02	1.3E-05
	Pb-210	8.4E-06	1.0E+00	2.0E+02	1.4E-02	2.4E-05
	Po-210	2.6E-05	1.0E+00	2.0E+02	1.4E-02	7.3E-05
	U-235	3.5E-07	4.6E-02	2.0E+02	1.4E-02	4.5E-08
					Total =	**1.1E-04**

Age Group	***Nuclide***	***Dcf; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
Age Group	***Nuclide***	***Dcf; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
1 - 2 yrs	U-238	1.2E-07	1.0E+00	2.6E+02	1.4E-02	4.4E-07
	U-234	1.3E-07	1.0E+00	2.6E+02	1.4E-02	4.7E-07
	Ra-226	9.6E-07	1.0E+00	2.6E+02	1.4E-02	3.5E-06
	Pb-210	3.6E-06	1.0E+00	2.6E+02	1.4E-02	1.3E-05
	Po-210	8.8E-06	1.0E+00	2.6E+02	1.4E-02	3.2E-05
	U-235	1.3E-07	4.6E-02	2.6E+02	1.4E-02	2.2E-08
					Total =	**4.9E-05**

Age Group	***Nuclide***	***Dcf; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
2 - 7 yrs	U-238	8.0E-08	1.0E+00	3.0E+02	7.1E-02	1.7E-06
	U-234	8.8E-08	1.0E+00	3.0E+02	7.1E-02	1.9E-06
	Ra-226	6.2E-07	1.0E+00	3.0E+02	7.1E-02	1.3E-05
	Pb-210	2.2E-06	1.0E+00	3.0E+02	7.1E-02	4.7E-05
	Po-210	4.4E-06	1.0E+00	3.0E+02	7.1E-02	9.4E-05
	U-235	8.5E-08	4.6E-02	3.0E+02	7.1E-02	8.3E-08
					Total =	**1.6E-04**

Age Group	***Nuclide***	***Dcf; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
7 - 12 yrs	U-238	6.8E-08	1.0E+00	3.5E+02	7.1E-02	1.7E-06
	U-234	7.4E-08	1.0E+00	3.5E+02	7.1E-02	1.8E-06
	Ra-226	8.0E-07	1.0E+00	3.5E+02	7.1E-02	2.0E-05
	Pb-210	1.9E-06	1.0E+00	3.5E+02	7.1E-02	4.7E-05
	Po-210	2.6E-06	1.0E+00	3.5E+02	7.1E-02	6.5E-05
	U-235	7.1E-08	4.6E-02	3.5E+02	7.1E-02	8.1E-08
					Total =	**1.3E-04**

Age Group	***Nuclide***	***Dcf; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
12 - 17 yrs	U-238	6.7E-08	1.0E+00	6.0E+02	7.1E-02	2.9E-06
	U-234	7.4E-08	1.0E+00	6.0E+02	7.1E-02	3.2E-06
	Ra-226	1.5E-06	1.0E+00	6.0E+02	7.1E-02	6.4E-05
	Pb-210	1.9E-06	1.0E+00	6.0E+02	7.1E-02	8.1E-05
	Po-210	1.6E-06	1.0E+00	6.0E+02	7.1E-02	6.8E-05
	U-235	7.0E-08	4.6E-02	6.0E+02	7.1E-02	1.4E-07
					Total =	**2.2E-04**

Age Group	***Nuclide***	***Dcf; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
> 17 yrs	U-238	4.5E-08	1.0E+00	7.3E+02	7.6E-01	2.5E-05

Age Group	*Nuclide*	*Dcf; Sv/Bq*	*Activity; Bq/L*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
	U-234	4.9E-08	1.0E+00	7.3E+02	7.6E-01	2.7E-05
	Ra-226	2.8E-07	1.0E+00	7.3E+02	7.6E-01	1.5E-04
	Pb-210	6.9E-07	1.0E+00	7.3E+02	7.6E-01	3.8E-04
	Po-210	1.2E-06	1.0E+00	7.3E+02	7.6E-01	6.6E-04
	U-235	4.7E-08	4.6E-02	7.3E+02	7.6E-01	1.2E-06
					Total =	**1.2E-03**

Lifetime average annual dose; D =	1.9E-03

The age group specific doses are obtained by simply replacing the age weighting factors with 1 in the tables above.

Table A3: Lifetime Average Dose Calculation using Method 1 Analysis

Age Group	*Nuclide*	*Dcf; Sv/Bq*	*Activity; Bq/L*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
0-1yrs	U-238	3.4E-07	1.0E+00	2.0E+02	1.0E+00	6.8E-05
	U-234	3.7E-07	1.0E+00	2.0E+02	1.0E+00	7.4E-05
	Ra-226	4.7E-06	1.0E+00	2.0E+02	1.0E+00	9.4E-04
	Pb-210	8.4E-06	1.0E+00	2.0E+02	1.0E+00	1.7E-03
	Po-210	2.6E-05	1.0E+00	2.0E+02	1.0E+00	5.2E-03
	U-235	3.5E-07	4.6E-02	2.0E+02	1.0E+00	3.2E-06
					Total =	**7.9E-03**

Age Group	*Nuclide*	*Dcf; Sv/Bq*	*Activity; Bq/L*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
1 - 2 yrs	U-238	1.2E-07	1.0E+00	2.6E+02	1.0E+00	3.1E-05
	U-234	1.3E-07	1.0E+00	2.6E+02	1.0E+00	3.4E-05
	Ra-226	9.6E-07	1.0E+00	2.6E+02	1.0E+00	2.5E-04
	Pb-210	3.6E-06	1.0E+00	2.6E+02	1.0E+00	9.4E-04
	Po-210	8.8E-06	1.0E+00	2.6E+02	1.0E+00	2.3E-03
	U-235	1.3E-07	4.6E-02	2.6E+02	1.0E+00	1.6E-06
					Total =	**3.5E-03**

Age Group	*Nuclide*	*Dcf; Sv/Bq*	*Activity; Bq/L*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
2 - 7 yrs	U-238	8.0E-08	1.0E+00	3.0E+02	1.0E+00	2.4E-05
	U-234	8.8E-08	1.0E+00	3.0E+02	1.0E+00	2.6E-05
	Ra-226	6.2E-07	1.0E+00	3.0E+02	1.0E+00	1.9E-04
	Pb-210	2.2E-06	1.0E+00	3.0E+02	1.0E+00	6.6E-04
	Po-210	4.4E-06	1.0E+00	3.0E+02	1.0E+00	1.3E-03
	U-235	8.5E-08	4.6E-02	3.0E+02	1.0E+00	1.2E-06

Age Group	Nuclide	Dcf; Sv/Bq	Activity; Bq/L	Water consumption; L/a	Weighting factor	Dose element; Sv/a
					Total =	**2.2E-03**

Age Group	Nuclide	Dcf; Sv/Bq	Activity; Bq/L	Water consumption; L/a	Weighting factor	Dose element; Sv/a
7 - 12 yrs	U-238	6.8E-08	1.0E+00	3.5E+02	1.0E+00	2.4E-05
	U-234	7.4E-08	1.0E+00	3.5E+02	1.0E+00	2.6E-05
	Ra-226	8.0E-07	1.0E+00	3.5E+02	1.0E+00	2.8E-04
	Pb-210	1.9E-06	1.0E+00	3.5E+02	1.0E+00	6.7E-04
	Po-210	2.6E-06	1.0E+00	3.5E+02	1.0E+00	9.1E-04
	U-235	7.1E-08	4.6E-02	3.5E+02	1.0E+00	1.1E-06
					Total =	**1.9E-03**

Age Group	Nuclide	Dcf; Sv/Bq	Activity; Bq/l	Water consumption; l/a	Weighting factor	Dose element; Sv/a
12 - 17 yrs	U-238	6.7E-08	1.0E+00	6.0E+02	1.0E+00	4.0E-05
	U-234	7.4E-08	1.0E+00	6.0E+02	1.0E+00	4.4E-05
	Ra-226	1.5E-06	1.0E+00	6.0E+02	1.0E+00	9.0E-04
	Pb-210	1.9E-06	1.0E+00	6.0E+02	1.0E+00	1.1E-03
	Po-210	1.6E-06	1.0E+00	6.0E+02	1.0E+00	9.6E-04
	U-235	7.0E-08	4.6E-02	6.0E+02	1.0E+00	1.9E-06
					Total =	**3.0E-03**

Age Group	Nuclide	Dcf; Sv/Bq	Activity; Bq/L	Water consumption; L/a	Weighting factor	Dose element; Sv/a
> 17 yrs	U-238	4.5E-08	1.0E+00	7.3E+02	1.0E+00	3.3E-05
	U-234	4.9E-08	1.0E+00	7.3E+02	1.0E+00	3.6E-05
	Ra-226	2.8E-07	1.0E+00	7.3E+02	1.0E+00	2.0E-04
	Pb-210	6.9E-07	1.0E+00	7.3E+02	1.0E+00	5.0E-04
	Po-210	1.2E-06	1.0E+00	7.3E+02	1.0E+00	8.8E-04
	U-235	4.7E-08	4.6E-02	7.3E+02	1.0E+00	1.6E-06
					Total =	**1.6E-03**

Method 2 - a detailed method

A water resource that is used by a large number of people would initially require a larger nuclide *measurement* vector; due to accuracy-required collective dose considerations. As soon as correlation can be demonstrated with the screening dose assessment Method 1, it can be used on a routine basis.

A default activity concentration equal to 1 Bq/L has again been inserted for the analysed nuclides in the tables.

Method 2 is similar to Method 1 except that larger measurement and calculation vectors are used.

Table A4: Lifetime Average Dose Calculation using Method 2 Analysis

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
0-1yrs	U-238	3.4E-07	1.0E+00	2.0E+02	1.4E-02	9.5E-07
	Th-234	4.0E-08	1.0E+00	2.0E+02	1.4E-02	1.1E-07
	Pa-234m	5.0E-09	1.0E+00	2.0E+02	1.4E-02	1.4E-08
	U-234	3.7E-07	1.0E+00	2.0E+02	1.4E-02	1.0E-06
	Th-230	4.1E-06	1.0E+00	2.0E+02	1.4E-02	1.1E-05
	Ra-226	4.7E-06	1.0E+00	2.0E+02	1.4E-02	1.3E-05
	Pb-210	8.4E-06	1.0E+00	2.0E+02	1.4E-02	2.4E-05
	Bi-210	1.5E-08	1.0E+00	2.0E+02	1.4E-02	4.2E-08
	Po-210	2.6E-05	1.0E+00	2.0E+02	1.4E-02	7.3E-05
	Th-232	4.6E-06	1.0E+00	2.0E+02	1.4E-02	1.3E-05
	Ra-228	3.0E-05	1.0E+00	2.0E+02	1.4E-02	8.4E-05
	Ac-228	7.4E-09	1.0E+00	2.0E+02	1.4E-02	2.1E-08
	Th-228	3.7E-06	1.0E+00	2.0E+02	1.4E-02	1.0E-05
	Ra-224	2.7E-06	1.0E+00	2.0E+02	1.4E-02	7.6E-06
	U-235	3.5E-07	1.0E+00	2.0E+02	1.4E-02	9.8E-07
	Th-231	3.9E-09	1.0E+00	2.0E+02	1.4E-02	1.1E-08
	Pa-231	1.3E-05	1.0E+00	2.0E+02	1.4E-02	3.6E-05
	Ac-227	3.3E-05	1.0E+00	2.0E+02	1.4E-02	9.2E-05
	Th-227	3.0E-07	1.0E+00	2.0E+02	1.4E-02	8.4E-07
	Ra-223	5.3E-06	1.0E+00	2.0E+02	1.4E-02	1.5E-05
					Total =	**3.8E-04**

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
1 - 2 yrs	U-238	1.2E-07	1.0E+00	2.6E+02	1.4E-02	4.4E-07
	Th-234	2.5E-08	1.0E+00	2.6E+02	1.4E-02	9.1E-08
	Pa-234m	3.2E-09	1.0E+00	2.6E+02	1.4E-02	1.2E-08
	U-234	1.3E-07	1.0E+00	2.6E+02	1.4E-02	4.7E-07
	Th-230	4.1E-07	1.0E+00	2.6E+02	1.4E-02	1.5E-06
	Ra-226	9.6E-07	1.0E+00	2.6E+02	1.4E-02	3.5E-06

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
	Pb-210	3.6E-06	1.0E+00	2.6E+02	1.4E-02	1.3E-05
	Bi-210	9.7E-09	1.0E+00	2.6E+02	1.4E-02	3.5E-08
	Po-210	8.8E-06	1.0E+00	2.6E+02	1.4E-02	3.2E-05
	Th-232	4.5E-07	1.0E+00	2.6E+02	1.4E-02	1.6E-06
	Ra-228	5.7E-06	1.0E+00	2.6E+02	1.4E-02	2.1E-05
	Ac-228	2.8E-09	1.0E+00	2.6E+02	1.4E-02	1.0E-08
	Th-228	3.7E-07	1.0E+00	2.6E+02	1.4E-02	1.3E-06
	Ra-224	6.6E-07	1.0E+00	2.6E+02	1.4E-02	2.4E-06
	U-235	1.3E-07	1.0E+00	2.6E+02	1.4E-02	4.7E-07
	Th-231	2.5E-09	1.0E+00	2.6E+02	1.4E-02	9.1E-09
	Pa-231	1.3E-06	1.0E+00	2.6E+02	1.4E-02	4.7E-06
	Ac-227	3.1E-06	1.0E+00	2.6E+02	1.4E-02	1.1E-05
	Th-227	7.0E-08	1.0E+00	2.6E+02	1.4E-02	2.5E-07
	Ra-223	1.1E-06	1.0E+00	2.6E+02	1.4E-02	4.0E-06
					Total =	**9.8E-05**

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
2 - 7 yrs	U-238	8.0E-08	1.0E+00	2.6E+02	1.4E-02	2.9E-07
	Th-234	1.3E-08	1.0E+00	3.0E+02	7.1E-02	2.8E-07
	Pa-234m	1.7E-09	1.0E+00	3.0E+02	7.1E-02	3.6E-08
	U-234	8.8E-08	1.0E+00	3.0E+02	7.1E-02	1.9E-06
	Th-230	3.1E-07	1.0E+00	3.0E+02	7.1E-02	6.6E-06
	Ra-226	6.2E-07	1.0E+00	3.0E+02	7.1E-02	1.3E-05
	Pb-210	2.2E-06	1.0E+00	3.0E+02	7.1E-02	4.7E-05
	Bi-210	4.8E-09	1.0E+00	3.0E+02	7.1E-02	1.0E-07
	Po-210	4.4E-06	1.0E+00	3.0E+02	7.1E-02	9.4E-05
	Th-232	3.5E-07	1.0E+00	3.0E+02	7.1E-02	7.5E-06
	Ra-228	3.4E-06	1.0E+00	3.0E+02	7.1E-02	7.2E-05
	Ac-228	1.4E-09	1.0E+00	3.0E+02	7.1E-02	3.0E-08
	Th-228	2.2E-07	1.0E+00	3.0E+02	7.1E-02	4.7E-06
	Ra-224	3.5E-07	1.0E+00	3.0E+02	7.1E-02	7.5E-06
	U-235	8.5E-08	1.0E+00	3.0E+02	7.1E-02	1.8E-06
	Th-231	1.2E-09	1.0E+00	3.0E+02	7.1E-02	2.6E-08
	Pa-231	1.1E-06	1.0E+00	3.0E+02	7.1E-02	2.3E-05
	Ac-227	2.2E-06	1.0E+00	3.0E+02	7.1E-02	4.7E-05
	Th-227	3.6E-08	1.0E+00	3.0E+02	7.1E-02	7.7E-07
	Ra-223	5.7E-07	1.0E+00	3.0E+02	7.1E-02	1.2E-05
					Total =	**3.4E-04**

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; Bq/L***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
7 - 12 yrs	U-238	6.8E-08	1.0E+00	3.5E+02	7.1E-02	1.7E-06
	Th-234	7.4E-09	1.0E+00	3.5E+02	7.1E-02	1.8E-07
	Pa-234m	1.0E-09	1.0E+00	3.5E+02	7.1E-02	2.5E-08
	U-234	7.4E-08	1.0E+00	3.5E+02	7.1E-02	1.8E-06

Age Group	*Nuclide*	*DCF; Sv/Bq*	*Activity; Bq/L*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
	Th-230	2.4E-07	1.0E+00	3.5E+02	7.1E-02	6.0E-06
	Ra-226	8.0E-07	1.0E+00	3.5E+02	7.1E-02	2.0E-05
	Pb-210	1.9E-06	1.0E+00	3.5E+02	7.1E-02	4.7E-05
	Bi-210	2.9E-09	1.0E+00	3.5E+02	7.1E-02	7.2E-08
	Po-210	2.6E-06	1.0E+00	3.5E+02	7.1E-02	6.5E-05
	Th-232	2.9E-07	1.0E+00	3.5E+02	7.1E-02	7.2E-06
	Ra-228	3.9E-06	1.0E+00	3.5E+02	7.1E-02	9.7E-05
	Ac-228	8.7E-10	1.0E+00	3.5E+02	7.1E-02	2.2E-08
	Th-228	1.5E-07	1.0E+00	3.5E+02	7.1E-02	3.7E-06
	Ra-224	2.6E-07	1.0E+00	3.5E+02	7.1E-02	6.5E-06
	U-235	7.1E-08	1.0E+00	3.5E+02	7.1E-02	1.8E-06
	Th-231	7.4E-10	1.0E+00	3.5E+02	7.1E-02	1.8E-08
	Pa-231	9.2E-07	1.0E+00	3.5E+02	7.1E-02	2.3E-05
	Ac-227	1.5E-06	1.0E+00	3.5E+02	7.1E-02	3.7E-05
	Th-227	2.3E-08	1.0E+00	3.5E+02	7.1E-02	5.7E-07
	Ra-223	4.5E-07	1.0E+00	3.5E+02	7.1E-02	1.1E-05
					Total =	**3.3E-04**

Age Group	*Nuclide*	*DCF; Sv/Bq*	*Activity; Bq/L*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
12 - 17 yrs	U-238	6.7E-08	1.0E+00	6.0E+02	7.1E-02	2.9E-06
	Th-234	4.2E-09	1.0E+00	6.0E+02	7.1E-02	1.8E-07
	Pa-234m	6.4E-10	1.0E+00	6.0E+02	7.1E-02	2.7E-08
	U-234	7.4E-08	1.0E+00	6.0E+02	7.1E-02	3.2E-06
	Th-230	2.2E-07	1.0E+00	6.0E+02	7.1E-02	9.4E-06
	Ra-226	1.5E-06	1.0E+00	6.0E+02	7.1E-02	6.4E-05
	Pb-210	1.9E-06	1.0E+00	6.0E+02	7.1E-02	8.1E-05
	Bi-210	1.6E-09	1.0E+00	6.0E+02	7.1E-02	6.8E-08
	Po-210	1.6E-06	1.0E+00	6.0E+02	7.1E-02	6.8E-05
	Th-232	2.5E-07	1.0E+00	6.0E+02	7.1E-02	1.1E-05
	Ra-228	5.3E-06	1.0E+00	6.0E+02	7.1E-02	2.3E-04
	Ac-228	5.3E-10	1.0E+00	6.0E+02	7.1E-02	2.3E-08
	Th-228	9.4E-08	1.0E+00	6.0E+02	7.1E-02	4.0E-06
	Ra-224	2.0E-07	1.0E+00	6.0E+02	7.1E-02	8.5E-06
	U-235	7.0E-08	1.0E+00	6.0E+02	7.1E-02	3.0E-06
	Th-231	4.2E-10	1.0E+00	6.0E+02	7.1E-02	1.8E-08
	Pa-231	8.0E-07	1.0E+00	6.0E+02	7.1E-02	3.4E-05
	Ac-227	1.2E-06	1.0E+00	6.0E+02	7.1E-02	5.1E-05
	Th-227	1.5E-08	1.0E+00	6.0E+02	7.1E-02	6.4E-07
	Ra-223	3.7E-07	1.0E+00	6.0E+02	7.1E-02	1.6E-05
					Total =	**5.8E-04**

Age Group	*Nuclide*	*DCF; Sv/Bq*	*Activity; Bq/L*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
> 17 yrs	U-238	4.5E-08	1.0E+00	7.3E+02	7.6E-01	2.5E-05
	Th-234	3.4E-09	1.0E+00	7.3E+02	7.6E-01	1.9E-06

Age Group	*Nuclide*	*DCF; Sv/Bq*	*Activity; Bq/L*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
	Pa-234m	5.1E-10	1.0E+00	7.3E+02	7.6E-01	2.8E-07
	U-234	4.9E-08	1.0E+00	7.3E+02	7.6E-01	2.7E-05
	Th-230	2.1E-07	1.0E+00	7.3E+02	7.6E-01	1.2E-04
	Ra-226	2.8E-07	1.0E+00	7.3E+02	7.6E-01	1.5E-04
	Pb-210	6.9E-07	1.0E+00	7.3E+02	7.6E-01	3.8E-04
	Bi-210	1.3E-09	1.0E+00	7.3E+02	7.6E-01	7.2E-07
	Po-210	1.2E-06	1.0E+00	7.3E+02	7.6E-01	6.6E-04
	Th-232	2.3E-07	1.0E+00	7.3E+02	7.6E-01	1.3E-04
	Ra-228	6.9E-07	1.0E+00	7.3E+02	7.6E-01	3.8E-04
	Ac-228	4.3E-10	1.0E+00	7.3E+02	7.6E-01	2.4E-07
	Th-228	7.2E-08	1.0E+00	7.3E+02	7.6E-01	4.0E-05
	Ra-224	6.5E-08	1.0E+00	7.3E+02	7.6E-01	3.6E-05
	U-235	4.7E-08	1.0E+00	7.3E+02	7.6E-01	2.6E-05
	Th-231	3.4E-10	1.0E+00	7.3E+02	7.6E-01	1.9E-07
	Pa-231	7.1E-07	1.0E+00	7.3E+02	7.6E-01	3.9E-04
	Ac-227	1.1E-06	1.0E+00	7.3E+02	7.6E-01	6.1E-04
	Th-227	8.8E-09	1.0E+00	7.3E+02	7.6E-01	4.9E-06
	Ra-223	0.0E+00	1.0E+00	7.3E+02	7.6E-01	0.0E+00
					Total =	**3.0E-03**

Lifetime average annual dose; D =	4.7E-03

The age group specific doses are obtained by simply replacing the age weighting factors with 1 in the tables above.

Table A5: Age Specific Dose Calculation using Method 2 Analysis

Age Group	*Nuclide*	*DCF; Sv/Bq*	*Activity; BqlL*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
0-1yrs	U-238	3.4E-07	1.0E+00	2.0E+02	1.0E+00	6.8E-05
	Th-234	4.0E-08	1.0E+00	2.0E+02	1.0E+00	8.0E-06
	Pa-234m	5.0E-09	1.0E+00	2.0E+02	1.0E+00	1.0E-06
	U-234	3.7E-07	1.0E+00	2.0E+02	1.0E+00	7.4E-05
	Th-230	4.1E-06	1.0E+00	2.0E+02	1.0E+00	8.2E-04
	Ra-226	4.7E-06	1.0E+00	2.0E+02	1.0E+00	9.4E-04
	Pb-210	8.4E-06	1.0E+00	2.0E+02	1.0E+00	1.7E-03
	Bi-210	1.5E-08	1.0E+00	2.0E+02	1.0E+00	3.0E-06
	Po-210	2.6E-05	1.0E+00	2.0E+02	1.0E+00	5.2E-03
	Th-232	4.6E-06	1.0E+00	2.0E+02	1.0E+00	9.2E-04
	Ra-228	3.0E-05	1.0E+00	2.0E+02	1.0E+00	6.0E-03
	Ac-228	7.4E-09	1.0E+00	2.0E+02	1.0E+00	1.5E-06
	Th-228	3.7E-06	1.0E+00	2.0E+02	1.0E+00	7.4E-04
	Ra-224	2.7E-06	1.0E+00	2.0E+02	1.0E+00	5.4E-04
	U-235	3.5E-07	1.0E+00	2.0E+02	1.0E+00	7.0E-05
	Th-231	3.9E-09	1.0E+00	2.0E+02	1.0E+00	7.8E-07
	Pa-231	1.3E-05	1.0E+00	2.0E+02	1.0E+00	2.6E-03
	Ac-227	3.3E-05	1.0E+00	2.0E+02	1.0E+00	6.6E-03
	Th-227	3.0E-07	1.0E+00	2.0E+02	1.0E+00	6.0E-05
	Ra-223	5.3E-06	1.0E+00	2.0E+02	1.0E+00	1.1E-03
					Total =	**2.7E-02**

Age Group	*Nuclide*	*DCF; Sv/Bq*	*Activity; BqlL*	*Water consumption; L/a*	*Weighting factor*	*Dose element; Sv/a*
1 - 2 yrs	U-238	1.2E-07	1.0E+00	2.6E+02	1.0E+00	3.1E-05
	Th-234	2.5E-08	1.0E+00	2.6E+02	1.0E+00	6.5E-06
	Pa-234m	3.2E-09	1.0E+00	2.6E+02	1.0E+00	8.3E-07
	U-234	1.3E-07	1.0E+00	2.6E+02	1.0E+00	3.4E-05
	Th-230	4.1E-07	1.0E+00	2.6E+02	1.0E+00	1.1E-04
	Ra-226	9.6E-07	1.0E+00	2.6E+02	1.0E+00	2.5E-04
	Pb-210	3.6E-06	1.0E+00	2.6E+02	1.0E+00	9.4E-04
	Bi-210	9.7E-09	1.0E+00	2.6E+02	1.0E+00	2.5E-06
	Po-210	8.8E-06	1.0E+00	2.6E+02	1.0E+00	2.3E-03
	Th-232	4.5E-07	1.0E+00	2.6E+02	1.0E+00	1.2E-04
	Ra-228	5.7E-06	1.0E+00	2.6E+02	1.0E+00	1.5E-03
	Ac-228	2.8E-09	1.0E+00	2.6E+02	1.0E+00	7.3E-07
	Th-228	3.7E-07	1.0E+00	2.6E+02	1.0E+00	9.6E-05
	Ra-224	6.6E-07	1.0E+00	2.6E+02	1.0E+00	1.7E-04
	U-235	1.3E-07	1.0E+00	2.6E+02	1.0E+00	3.4E-05
	Th-231	2.5E-09	1.0E+00	2.6E+02	1.0E+00	6.5E-07
	Pa-231	1.3E-06	1.0E+00	2.6E+02	1.0E+00	3.4E-04

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; BqlL***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
	Ac-227	3.1E-06	1.0E+00	2.6E+02	1.0E+00	8.1E-04
	Th-227	7.0E-08	1.0E+00	2.6E+02	1.0E+00	1.8E-05
	Ra-223	1.1E-06	1.0E+00	2.6E+02	1.0E+00	2.9E-04
					Total =	**7.0E-03**

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; BqlL***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
2 - 7 yrs	U-238	8.0E-08	1.0E+00	2.6E+02	1.0E+00	2.1E-05
	Th-234	1.3E-08	1.0E+00	3.0E+02	1.0E+00	3.9E-06
	Pa-234m	1.7E-09	1.0E+00	3.0E+02	1.0E+00	5.1E-07
	U-234	8.8E-08	1.0E+00	3.0E+02	1.0E+00	2.6E-05
	Th-230	3.1E-07	1.0E+00	3.0E+02	1.0E+00	9.3E-05
	Ra-226	6.2E-07	1.0E+00	3.0E+02	1.0E+00	1.9E-04
	Pb-210	2.2E-06	1.0E+00	3.0E+02	1.0E+00	6.6E-04
	Bi-210	4.8E-09	1.0E+00	3.0E+02	1.0E+00	1.4E-06
	Po-210	4.4E-06	1.0E+00	3.0E+02	1.0E+00	1.3E-03
	Th-232	3.5E-07	1.0E+00	3.0E+02	1.0E+00	1.1E-04
	Ra-228	3.4E-06	1.0E+00	3.0E+02	1.0E+00	1.0E-03
	Ac-228	1.4E-09	1.0E+00	3.0E+02	1.0E+00	4.2E-07
	Th-228	2.2E-07	1.0E+00	3.0E+02	1.0E+00	6.6E-05
	Ra-224	3.5E-07	1.0E+00	3.0E+02	1.0E+00	1.1E-04
	U-235	8.5E-08	1.0E+00	3.0E+02	1.0E+00	2.6E-05
	Th-231	1.2E-09	1.0E+00	3.0E+02	1.0E+00	3.6E-07
	Pa-231	1.1E-06	1.0E+00	3.0E+02	1.0E+00	3.3E-04
	Ac-227	2.2E-06	1.0E+00	3.0E+02	1.0E+00	6.6E-04
	Th-227	3.6E-08	1.0E+00	3.0E+02	1.0E+00	1.1E-05
	Ra-223	5.7E-07	1.0E+00	3.0E+02	1.0E+00	1.7E-04
					Total =	**4.8E-03**

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; BqlL***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
7 - 12 yrs	U-238	6.8E-08	1.0E+00	3.5E+02	1.0E+00	2.4E-05
	Th-234	7.4E-09	1.0E+00	3.5E+02	1.0E+00	2.6E-06
	Pa-234m	1.0E-09	1.0E+00	3.5E+02	1.0E+00	3.5E-07
	U-234	7.4E-08	1.0E+00	3.5E+02	1.0E+00	2.6E-05
	Th-230	2.4E-07	1.0E+00	3.5E+02	1.0E+00	8.4E-05
	Ra-226	8.0E-07	1.0E+00	3.5E+02	1.0E+00	2.8E-04
	Pb-210	1.9E-06	1.0E+00	3.5E+02	1.0E+00	6.7E-04
	Bi-210	2.9E-09	1.0E+00	3.5E+02	1.0E+00	1.0E-06
	Po-210	2.6E-06	1.0E+00	3.5E+02	1.0E+00	9.1E-04
	Th-232	2.9E-07	1.0E+00	3.5E+02	1.0E+00	1.0E-04
	Ra-228	3.9E-06	1.0E+00	3.5E+02	1.0E+00	1.4E-03
	Ac-228	8.7E-10	1.0E+00	3.5E+02	1.0E+00	3.0E-07
	Th-228	1.5E-07	1.0E+00	3.5E+02	1.0E+00	5.3E-05
	Ra-224	2.6E-07	1.0E+00	3.5E+02	1.0E+00	9.1E-05
	U-235	7.1E-08	1.0E+00	3.5E+02	1.0E+00	2.5E-05

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; BqlL***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
	Th-231	7.4E-10	1.0E+00	3.5E+02	1.0E+00	2.6E-07
	Pa-231	9.2E-07	1.0E+00	3.5E+02	1.0E+00	3.2E-04
	Ac-227	1.5E-06	1.0E+00	3.5E+02	1.0E+00	5.3E-04
	Th-227	2.3E-08	1.0E+00	3.5E+02	1.0E+00	8.1E-06
	Ra-223	4.5E-07	1.0E+00	3.5E+02	1.0E+00	1.6E-04
					Total =	**4.6E-03**

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; BqlL***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
12 - 17 yrs	U-238	6.7E-08	1.0E+00	6.0E+02	1.0E+00	4.0E-05
	Th-234	4.2E-09	1.0E+00	6.0E+02	1.0E+00	2.5E-06
	Pa-234m	6.4E-10	1.0E+00	6.0E+02	1.0E+00	3.8E-07
	U-234	7.4E-08	1.0E+00	6.0E+02	1.0E+00	4.4E-05
	Th-230	2.2E-07	1.0E+00	6.0E+02	1.0E+00	1.3E-04
	Ra-226	1.5E-06	1.0E+00	6.0E+02	1.0E+00	9.0E-04
	Pb-210	1.9E-06	1.0E+00	6.0E+02	1.0E+00	1.1E-03
	Bi-210	1.6E-09	1.0E+00	6.0E+02	1.0E+00	9.6E-07
	Po-210	1.6E-06	1.0E+00	6.0E+02	1.0E+00	9.6E-04
	Th-232	2.5E-07	1.0E+00	6.0E+02	1.0E+00	1.5E-04
	Ra-228	5.3E-06	1.0E+00	6.0E+02	1.0E+00	3.2E-03
	Ac-228	5.3E-10	1.0E+00	6.0E+02	1.0E+00	3.2E-07
	Th-228	9.4E-08	1.0E+00	6.0E+02	1.0E+00	5.6E-05
	Ra-224	2.0E-07	1.0E+00	6.0E+02	1.0E+00	1.2E-04
	U-235	7.0E-08	1.0E+00	6.0E+02	1.0E+00	4.2E-05
	Th-231	4.2E-10	1.0E+00	6.0E+02	1.0E+00	2.5E-07
	Pa-231	8.0E-07	1.0E+00	6.0E+02	1.0E+00	4.8E-04
	Ac-227	1.2E-06	1.0E+00	6.0E+02	1.0E+00	7.2E-04
	Th-227	1.5E-08	1.0E+00	6.0E+02	1.0E+00	9.0E-06
	Ra-223	3.7E-07	1.0E+00	6.0E+02	1.0E+00	2.2E-04
					Total =	**8.2E-03**

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; BqlL***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
> 17 yrs	U-238	4.5E-08	1.0E+00	7.3E+02	1.0E+00	3.3E-05
	Th-234	3.4E-09	1.0E+00	7.3E+02	1.0E+00	2.5E-06
	Pa-234m	5.1E-10	1.0E+00	7.3E+02	1.0E+00	3.7E-07
	U-234	4.9E-08	1.0E+00	7.3E+02	1.0E+00	3.6E-05
	Th-230	2.1E-07	1.0E+00	7.3E+02	1.0E+00	1.5E-04
	Ra-226	2.8E-07	1.0E+00	7.3E+02	1.0E+00	2.0E-04
	Pb-210	6.9E-07	1.0E+00	7.3E+02	1.0E+00	5.0E-04
	Bi-210	1.3E-09	1.0E+00	7.3E+02	1.0E+00	9.5E-07
	Po-210	1.2E-06	1.0E+00	7.3E+02	1.0E+00	8.8E-04
	Th-232	2.3E-07	1.0E+00	7.3E+02	1.0E+00	1.7E-04
	Ra-228	6.9E-07	1.0E+00	7.3E+02	1.0E+00	5.0E-04
	Ac-228	4.3E-10	1.0E+00	7.3E+02	1.0E+00	3.1E-07
	Th-228	7.2E-08	1.0E+00	7.3E+02	1.0E+00	5.3E-05

Age Group	***Nuclide***	***DCF; Sv/Bq***	***Activity; BqlL***	***Water consumption; L/a***	***Weighting factor***	***Dose element; Sv/a***
	Ra-224	6.5E-08	1.0E+00	7.3E+02	1.0E+00	4.7E-05
	U-235	4.7E-08	1.0E+00	7.3E+02	1.0E+00	3.4E-05
	Th-231	3.4E-10	1.0E+00	7.3E+02	1.0E+00	2.5E-07
	Pa-231	7.1E-07	1.0E+00	7.3E+02	1.0E+00	5.2E-04
	Ac-227	1.1E-06	1.0E+00	7.3E+02	1.0E+00	8.0E-04
	Th-227	8.8E-09	1.0E+00	7.3E+02	1.0E+00	6.4E-06
	Ra-223	0.0E+00	1.0E+00	7.3E+02	1.0E+00	0.0E+00
					Total =	**3.9E-03**