ENVIRONMENTAL RADIATION IN NAMIBIA

1.1 INTRODUCTION

Radiation is travelling energy, and occurs in nature in the form of electromagnetic waves and sub-atomic particles [von Oertzen, 2010b]. Every day, humans benefit from the many different forms of low-energy electromagnetic radiation: its spectrum includes long-wavelength radio waves, microwaves used in kitchen appliances, as well as infrared, visible light and ultraviolet radiation. These forms of low-energy radiation are all referred to as 'non-ionising' because they lack the energy to ionise matter, i.e. remove electrons from the shells of atoms.

Ionising radiation on the other hand is associated with high-energy x-rays and gamma rays, and the various types of radiation emitted by radioactive elements. Ionising radiation has sufficient energy to strip electrons from atoms, resulting in electrically charged particles which are called ions. It has long been recognised that large doses of ionising radiation can damage human cells and tissue: free-roaming ions created at the cellular level are highly reactive and may trigger or participate in chemical reactions, some of which may bring about molecular bonds which are harmful to the cell. For example, chemical reactions that are activated by ions generated by ionising radiation can alter the chemical balance of natural processes, which may give rise to undesirable chemical products and thereby negatively affect living cells. In addition, ionising radiation can change the make-up of cells by changing the genetic building blocks of cells and in this way bring about cancerous cell multiplication and growth.

Not all atomic nuclei found in nature are stable. When unstable nuclei undergo a process of nuclear rearrangement they emit particles and radiation. The process whereby radiation is emitted from atomic nuclei as a result of nuclear instability is called radioactivity. The most common types of sub-atomic particles and radiation emitted during radioactive decays of atomic nuclei are alpha particles, beta particles and gamma radiation. Radioactivity is a natural phenomenon, and elements such as uranium, thorium and potassium are naturally occurring radioactive substances.

Radioactivity and the effects of ionising radiation on living tissue have been studied for many decades. Today it is well recognised that an exposure to large doses of ionising radiation may have potentially damaging effects on humans. To ensure that the voluntary and accidental exposure to ionising radiation is adequately regulated, the International X-ray and Radium

Protection Committee was established in 1928. This body was later renamed the International Commission on Radiological Protection (ICRP). Its purpose is to establish basic principles for and issue recommendations on radiation protection, which today form the basis for international as well as national regulations governing the exposure of radiation workers and members of the public. The ICRP's recommendations have also been incorporated by the International Atomic Energy Agency (IAEA) into its Basic Safety Standards for Radiation Protection, which are published jointly with the World Health Organisation (WHO), the International Labour Organisation (ILO) and the Nuclear Energy Agency (NEA). Today, these standards are used worldwide to ensure radiation safety and protection for workers who may be occupationally exposed to ionising radiation, as well as for members of the general public.

In 1955, the General Assembly of the United Nations formed an inter-governmental body known as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). UNSCEAR is tasked to assemble, study and disseminate information on observed levels of ionising radiation and radioactivity (both natural and man-made) in the environment, and on the effects of such radiation on humans and the environment. Many of the UNSCEAR reports are regularly used to guide assessments of exposures to radiation.

Today, the basic approaches to radiation protection are consistent all over the world. The ICRP recommends that any exposure above natural background radiation should be kept as low as reasonably achievable, as well as below individual dose limits specified separately for workers and members of the public. The individual dose limit for radiation workers averaged over 5 years is 20 mSv per year, while the incremental dose limit for members of the public, i.e. the dose over and above the natural background radiation, is set at 1 mSv per year. These dose limits are based on the realisation that there is no discernible threshold dose below which there would no longer be a potentially harmful effect due to exposure to ionising radiation, and are put forward as an expression of a precautionary approach that guides the radiation sector.

Namibian regulatory requirements governing radiation protection are based on the recommendations of the ICRP and IAEA, which implies that individual doses to members of the public must be kept as low as reasonably achievable, and that consideration must also be given to the presence of other sources of ionising radiation that may cause additional exposure to radiation to the same group. Also, allowance for future sources and practices must be made, so that the total dose received by an individual member of the public does not exceed the set dose limit. This is an important stipulation, especially in a geographical area that is likely to see several uranium mines operate simultaneously, as it has direct implications for how radiation protection measures are applied during the construction, operational and decommissioning phases of each uranium mine.

1.2 NATURAL BACKGROUND RADIATION

Many areas throughout the world experience high levels of natural background radiation. Indeed, parts of the Erongo Region in Namibia are known to have high levels of natural background radiation, especially of terrestrial origin [von Oertzen, 2010a]. This is not entirely unexpected, as the Erongo Region is also called the "Uranium Province of Namibia" [SEA, 2010].

Natural sources of ionising radiation include radiation of extra-terrestrial origin, i.e. cosmic radiation, and radiation emitted by soils, rocks and groundwater, i.e. terrestrial radiation, as well as radiation from radioactive dust and radioactive gases such as radon and thoron. Humans are continuously exposed to ionising radiation of natural and man-made origin. Such exposure is location- and time-dependent, and any potential effects depend on the exposure dose received by an individual person. To quantify the total exposure to ionising radiation that members of the public are exposed to one has to determine the magnitude of the exposure to the prevailing natural background radiation and add to it the incremental contribution of additional sources, such as a uranium mine.

The contribution from **cosmic radiation** to the natural background radiation levels depends on the geographic location of the receptor. Typically in Namibia, exposure doses from cosmic radiation range between 0.3 $mSv.a^{-1}$ at the coast to approximately 0.7 $mSv.a^{-1}$ in the central highlands [Wackerle, 2009a]. Since most people living in the Erongo Region live in coastal cities and towns (Walvis Bay, Swakopmund, Henties Bay), the population-weighted[1] average of the cosmic radiation for the Region is similar to the population-weighted world average of 0.38 $mSv.a^{-1}$, as reported by UNSCEAR [UNSCEAR, 1993]. Figure 1 depicts the contribution of cosmic radiation to the natural background radiation in Namibia, and is expressed in mSv per annum ($mSv.a^{-1}$).

[1] The population-weighted average dose takes cognizance of the relative population sizes exposed to specific doses, and then averages over the entire population living in the area under consideration.

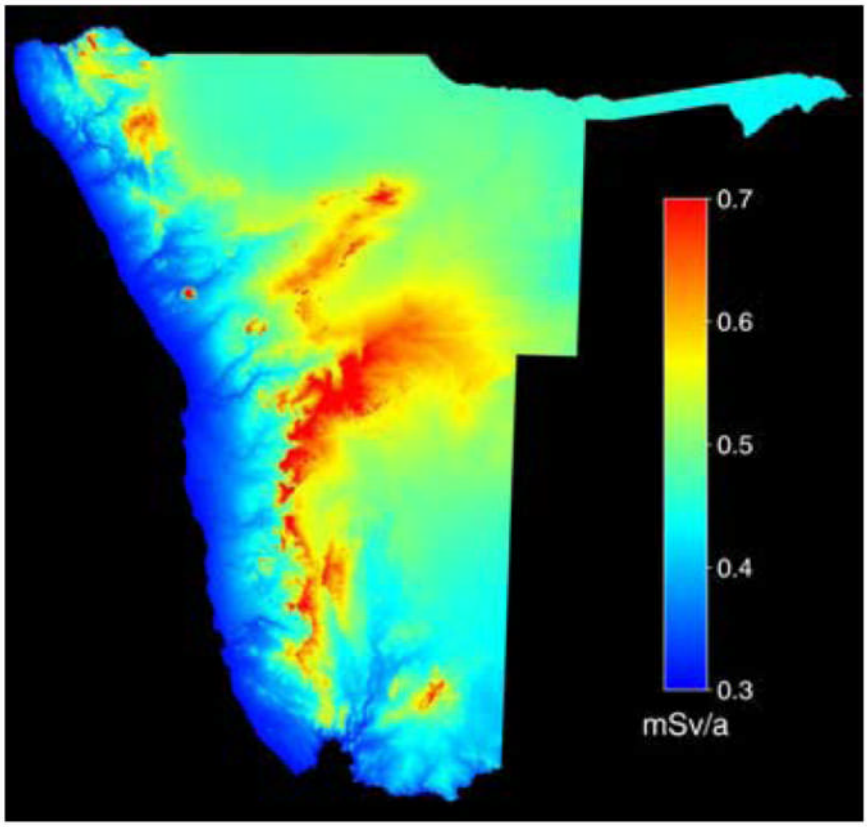

Figure 1: Contribution of cosmic radiation to natural background radiation in Namibia, shown in mSv/a (mSv.a^{-1}) [Wackerle, 2009a]

The contribution of **terrestrial sources** to the natural background radiation in the Erongo Region is obtained from the assessment of airborne radiometric surveys [Wackerle, 2009b]. A preliminary figure for the dose rate from natural terrestrial gamma background radiation in the Erongo Region ranges between close to zero up to 7.3 mSv.a^{-1}, with a regional average of 0.7 mSv.a^{-1} [Wackerle, 2009b]. The regional average is therefore about double the global average terrestrial radiation dose rate of 0.33 mSv.a^{-1}. The population-weighted average of the contribution of the natural terrestrial radiation in the Erongo Region is however lower than the average terrestrial radiation in the Region, again as a consequence of most inhabitants living in coastal towns where terrestrial radiation levels tend to be lower than the average for the Region. The population-weighted average natural terrestrial gamma radiation exposure in the Erongo Region is therefore comparable to the world average value of 0.48 mSv.a^{-1}, as reported by UNSCEAR [UNSCEAR, 1993]. Figure 2 depicts the contribution of terrestrial radiation to the natural background radiation in Namibia, and is expressed in mSv.a^{-1}.

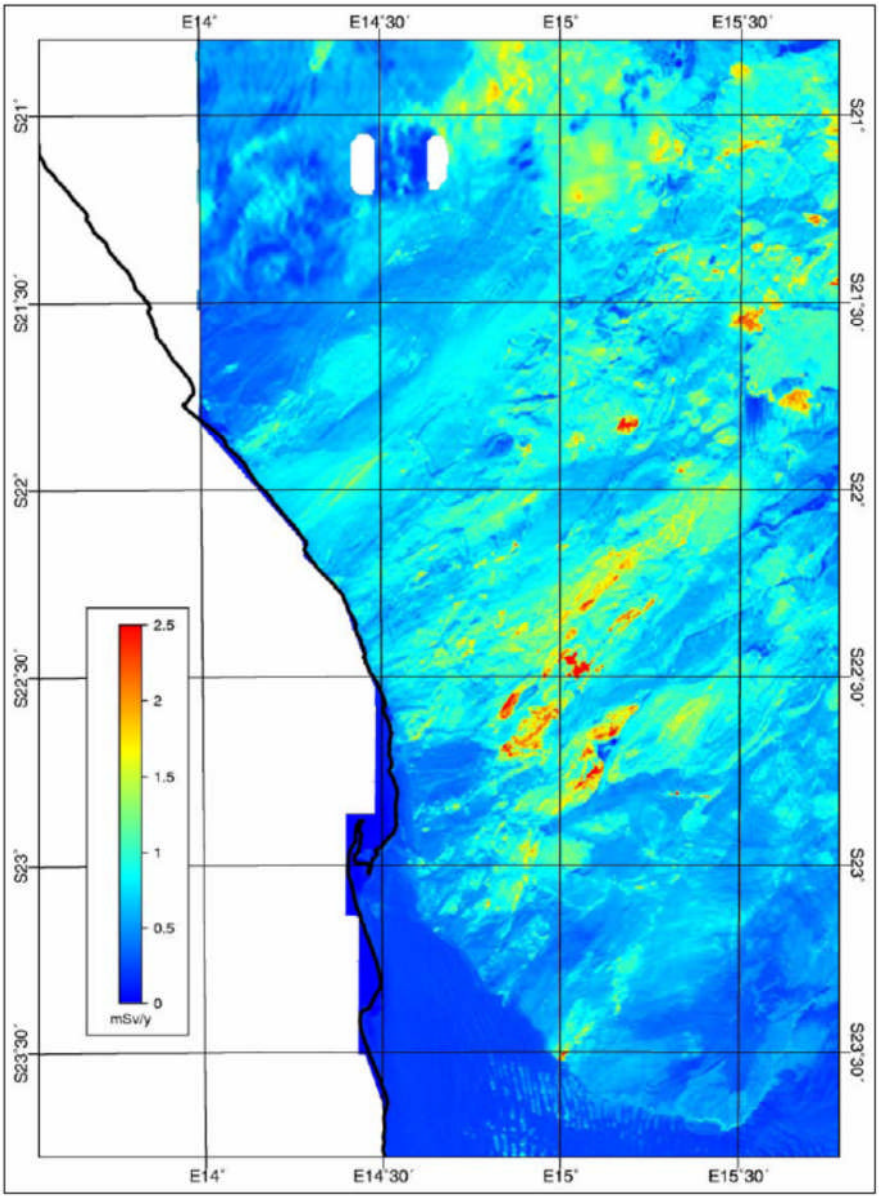

Figure 2: Contribution of terrestrial radiation to the natural background radiation in Namibia, expressed in mSv/y (mSv.a^{-1}) [Wackerle, 2009b]

Other forms of background radiation in the Erongo Region originate from **radioactive dust**, and from radon with its radioactive decay products. The contribution of radioactive dust to the natural background radiation is important in the context of an environmental assessment for a uranium mine in the central Namib. Dust is generated in copious amounts in the mining processes, and can be inhaled, and dust remains airborne for considerable periods in the generally dry in-land air characteristic of much of the Erongo Region.

The contribution of radioactive dust to the natural background radiation was recently measured as part of the Strategic Environmental Assessment, and the Erongo Regional average is some ten times the world average of 0.0058 mSv.a^{-1} [SEA, 2010]. Figure 3 depicts the contribution of radioactive dust to the natural background radiation in the Erongo Region of

Namibia, in mSv.a^{-1} [van Blerk *et al.*, 2010], where it is noted that the baseline contribution of dust is due to natural background sources of dust plus those produced by the existing uranium mines, most notably Rössing Uranium and Langer Heinrich Uranium.

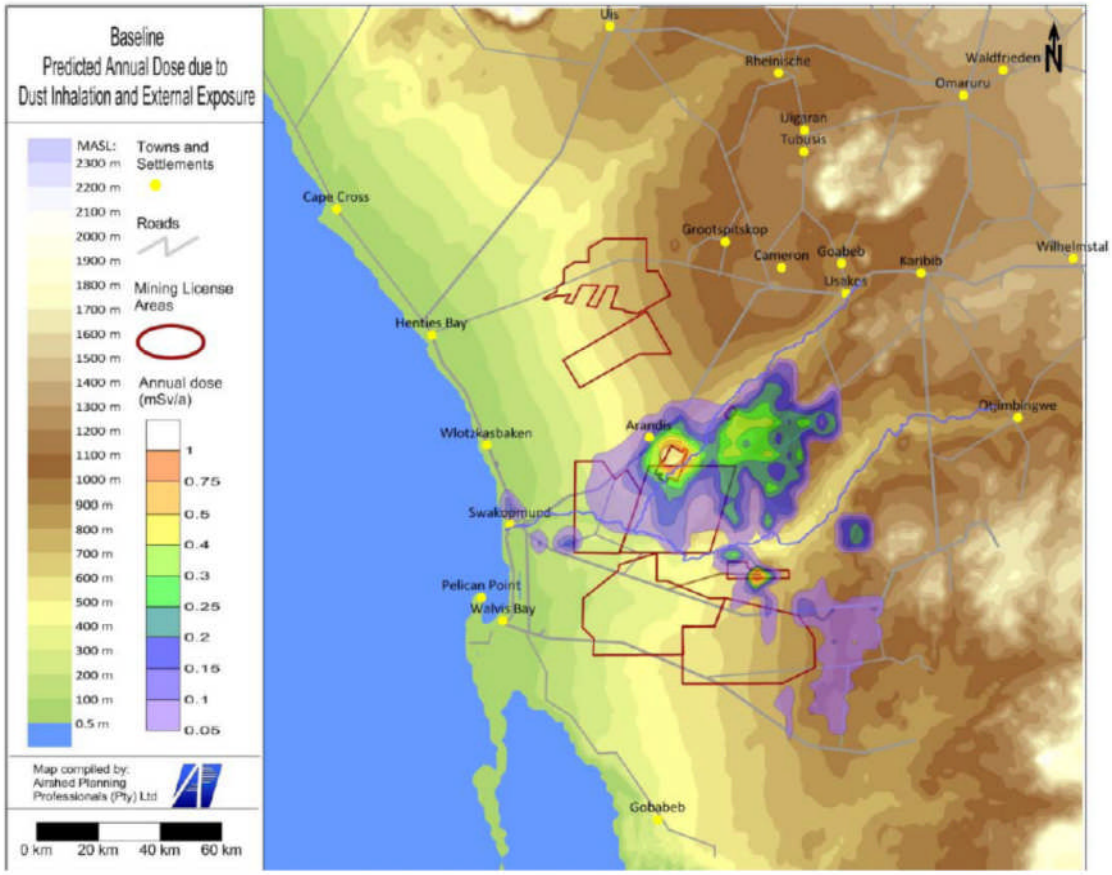

Figure 3: Contribution of radioactive dust to the natural background radiation in the Erongo Region [van Blerk *et al.*, 2010]

Radon (Rn^{222} and Rn^{220}) is a gas and is formed in soils through the radioactive decay of radium (Ra^{226} and Ra^{224}). Radon and its decay products are found in variable concentrations both indoors and outdoors, and are known to exist in many mining environments. The concentration of radon in the Erongo Region was measured in a regional radon monitoring programme conducted as part of the recently completed Strategic Environmental Assessment [SEA, 2010]. It was found that the average regional radon inhalation dose measured over the 9 month period (August 2009 to April 2010) was 0.46 mSv.a^{-1}. It is noted that this baseline radon inhalation dose is due to natural background exhalations plus those produced by the existing uranium mines, most notably Rössing Uranium and Langer Heinrich Uranium.

As yet, little information is available for the Erongo Region to determine a baseline dose due to the **ingestion of radionuclides**, either directly through the consumption of food or via the intake of water. The population-weighted world average exposure dose as reported by

UNSCEAR due to ingestion is 0.31 mSv.a^{-1} [UNSCEAR, 1993], and is assumed to be very similar in the Erongo Region of Namibia.

Exposure to **man-made sources of radiation**, including medical exposures and exposures due to the use of consumer products, lifestyle choices such as smoking and flying, are well researched in the international context. Reliable baseline data however is not readily available for Namibia in general or for the Erongo Region in particular. The world average radiation dose from medical diagnostic procedures is 0.4 mSv.a^{-1}, but this is an average over the whole world population without any distinction between national health care levels across countries. UNSCEAR classifies Namibia as having health care level III, which corresponds to 1 physician for every 1,000 to 3,000 members of the population. The average dose to the Namibian population due to x-ray procedures is reported to be 0.02 mSv.a^{-1}, and nuclear medicine procedures are not reported at all. The Namibian average medical exposure dose therefore corresponds to only about 5% of the population-weighted world average figure. However, significant variations in individual exposures can be expected in Namibia, mainly because of the large differences in access to health care services between Namibians of different income levels.

Table 1 below summarises the various exposure contributions due to natural and man-made sources of ionising radiation, and allows for a comparison between such values in the Erongo Region and the population- and age-weighted world averages.

Source	Erongo Region [mSv.a^{-1}]	World Average [mSv.a^{-1}]
Cosmic radiation	0.35	0.38
Terrestrial radiation	0.55	0.48
Radioactive dust	0.05	0.0058
Radon	0.5 (regional average, highly time- and position-dependent)	1.095
Ingestion	0.3 (assume to be similar to world average)	0.31
Sub-total for natural sources	**1.75**	**2.27**
Medical x-rays	0.02	0.37
Nuclear medicine	assume 0.001	0.03
Consumer products	assume 0.01	0.06
Nuclear weapons testing & production	assume 0.0046	0.0046
Nuclear fuel cycle	assume 0.0002	0.0002
Sub-total for man-made sources	**~0.04**	**0.46**
GRAND TOTAL	**~1.8**	**2.7**

Table 1: A comparison of the population-averaged human exposure to natural and man-made sources of radiation in the Erongo Region and the World [von Oertzen, 2010b]

1.3 RADIONUCLIDES IN WATER

1.3.1 Introduction

The interpretation of the radiological risks posed by the presence of radionuclides in water requires some understanding of the behaviour of these nuclides when in slow-moving water resources. In closed systems, the progeny of uranium and thorium are present in concentrations that are determined by the concentrations of the uranium and thorium parent isotopes and the time since the system under consideration became closed to radionuclide transport and migration.

In nature, completely closed systems rarely exist, and predictions regarding radionuclide concentrations in water bodies invariably include considerable uncertainties. Generally, radionuclides and their decay products are found in groundwater in element-specific concentrations, dependent on complex hydro-geological processes and conditions, including dissolution rates, transport and ion-exchange processes as well as redox potentials and pH-conditions of the aqueous system. Such hydro-geological processes result in non-equilibrium conditions between parent nuclides, and their progeny.

In the oxidised zone of the earth's near-surface environment, uranium and thorium may both be mobilised, although in different ways. Uranium may either move in a detrital, resistate phase, or in solution as a complex ion. Thorium on the other hand has an extremely low solubility in natural water and there is a close correlation of thorium concentrations and the detrital content of water. Thorium is almost entirely transported in particulate form, and is either bound in insoluble resistate minerals or is adsorbed on the surface of clay minerals. Even when thorium, such as for example Th-230, is generated in solution by the radioactive decay of uranium-234, it rapidly hydrolyses and adsorbs onto the nearest solid surface. Both uranium and thorium appear in the 4+ oxidation state in primary igneous rocks and minerals, but uranium, unlike thorium, 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 uranium transport during weathering.

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

1.3.2 Uranium in regional water bodies

The Strategic Environmental Assessment has commissioned several studies to obtain a comprehensive picture of the groundwater resources in the Erongo Region, and the ambient water quality [SEA, 2010]. These studies have generated significant new insights into the characteristics of groundwater flows in the alluvial aquifers, the modes of recharge, and water

quality in the Erongo Region. However, the potential radiological dose from groundwater has not yet been calculated. As groundwater resources are scarce in the hyper-arid environment of the Namib, it is imperative that the risk of pollution from mining operations on groundwater resources is well understood, and that preventative measures are in place to ensure that groundwater extraction rates remain within the known sustainable extraction limits. As yet however, the potential risks of radiological contamination of groundwater resources cannot be comprehensively quantified, although there is some consensus that current mining operations have not added measurable quantities of radionuclides to the groundwater.

Part of the difficulty in characterising radionuclides in groundwater is that uranium found in the aquatic environment cannot always be assigned clearly to a particular source. The identification of sources however, is important in order to distinguish between natural background concentrations resulting from natural leaching, dispersion and transport of uranium, and potential sources of contamination from mining activities or specific pollution events. Potential sources of uranium in groundwater are primary uranium deposits (bedrock), uranium originating from paleo-channels (saline aquatic environment), secondary uranium precipitates in calcrete (carnotite), treated uranium (sodium bicarbonate/sulphuric acid process), and uranium and other radionuclides leached from tailings.

In order to overcome this difficulty, the Strategic Environmental Assessment used naturally occurring radioactive and stable isotopes as environmental tracers for the localisation and the assessment of the presence of natural or mine-induced radionuclides in groundwater. Samples of groundwater, sediment and mine tailings were taken to determine whether the radionuclides in groundwater were from natural or mine-induced sources.

One study undertaken as part of the Strategic Environmental Assessment found that uranium is a common trace element in all 78 water samples collected along the length of the Khan and Swakop rivers [Kringel *et al.*, 2010]. Furthermore, the study found that the natural background concentration of uranium ranges between 2 $\mu g.l^{-1}$ and 528 $\mu g.l^{-1}$ in the alluvial groundwater, with a mean of 39 $\mu g.l^{-1}$. It is to be noted that these values are well above the World Health Organisation Provisional Guideline Value for Drinking Water, which is 15 $\mu g.l^{-1}$ [WHO, 2003]. However, the Namibian Group A water quality limit of 1,000 $\mu g.l^{-1}$ was not exceeded. It was also found that saline water samples from lower Swakop River catchment generally exhibited higher uranium concentrations than the respective samples found in the headwater regions.

The Strategic Environmental Assessment concluded that groundwater in the headwater region of the Swakop River valley and in the valley upstream of the Langer Heinrich Uranium Mine shows low uranium concentrations, with values below the WHO guideline, while uranium concentrations in the Khan River valley are generally higher than in the Swakop River alluvial valley. The uranium concentrations in freshwater samples from the upper Khan River valley are generally above the WHO guideline value. Also, saline water in the lower part of the Khan River valley and the Swakop River valley downstream from the confluence has uranium concentrations of up to 230 $\mu g.l^{-1}$. Altogether six groundwater samples have uranium concentrations exceeding 230 $\mu g.l^{-1}$. Three of the sampling points are located in the vicinity of

Rössing Uranium Mine, one near Langer Heinrich Uranium Mine, and two samples are from wells in the Swakop river valley downstream of the confluence of the Swakop and Khan rivers.

Process and seepage water samples from the Langer Heinrich Uranium Mine are alkaline sodium-carbonate waters, with very high concentrations of uranium, arsenic and fluoride. The samples from the Rössing Uranium Mine premises are acidic solutions with elevated concentrations of uranium, manganese and a number of trace elements like lithium, niobium and cobalt. At both sites, samples from observation wells show no clear indication of contamination by process waters.

In another study undertaken as part of the Strategic Environmental Assessment, the authors investigated radon concentrations in groundwater [Schubert *et al.*, 2010]. It is known that radon (Rn^{222}) is a good environmental tracer, mainly due to its chemically inert behaviour (appearing as a dissolved noble gas), its ubiquitous occurrence in the environment, and its straightforward detectability. In addition, because radon is a direct progeny of radium (Ra^{226}), it is a useful indicator of natural radionuclide contaminations emanating from the uranium (U^{238}) decay chain. The study analysed forty water samples for Rn^{222}, and radon concentrations of between 0.5 and 28 $Bq.l^{-1}$ were found. Given that the Ra^{226} background activity concentration detected in the sediment of the Swakop River valley was found to be about 25 $Bq.kg^{-1}$, the study states that none of the radon concentrations detected in the tested groundwater exceeded the natural background level. It is interesting to note that upstream radon data revealed background concentrations of up to 20 $Bq.l^{-1}$ (20 km north-east of Rössing on the Khan River), while water taken from wells close to the Rössing Uranium Mine showed concentrations of around 13 $Bq.l^{-1}$. The highest radon concentration was found in a well located some 9 km downstream of the Langer Heinrich uranium mine at the confluence of the Gawib and Swakop rivers, at a value of 28 $Bq.l^{-1}$. However, the study also concluded that this sample did not show any mine-induced chemical peculiarities.

A preliminary conclusion of the groundwater studies undertaken as part of the Strategic Environmental Assessment indicates that there is a very low risk of radiological exposure from contaminated groundwater in the lower Swakop River for three main reasons [SEA, 2010]:

1. the Swakop and Khan Rivers are not homogeneous aquifers, but separated into compartments. These compartments are mostly dominated by vertical flow components which manifest themselves as evapo-transpiration and recharge components. Stored water volumes are only replenished by occasional flood events and the resulting recharge. This implies that lateral or downstream flow of water in the alluvial aquifers is extremely slow (on timescales of the order of decades), and any pollution event would be 'caught' within an affected compartment.

2. natural uranium is ubiquitous in the catchment area of the Swakop and Khan Rivers. Concentrations of uranium in the upper and middle parts of these rivers tend to be lower than in their lower parts, with some exceptions, and uranium concentrations tend

to increase towards the lowest parts of the Swakop and Khan Rivers, again with some exceptions. This seems to suggest that the uranium found in the alluvial aquifers is of geogenic rather than anthropogenic origin.

3. the radon distribution pattern mapped in the Khan and Swakop River valleys, and the radionuclide concentrations detected in the tailings materials of Langer Heinrich uranium mine and Rössing Uranium mine do not indicate seepage of tailings water into the alluvial aquifers. Radon concentrations appear to correspond with the radium background concentration typical of the sediments in the surrounding river beds.

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