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Report on the evaluation of the evidence on radiological water quality to inform the update to the 2008 NHMRC Guidelines for Managing Risks in Recreational Water

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ARPANSA
619 Lower Plenty Road
YALLAMBIE VIC 3085
Tel: 1800 022 333 (Freecall) or +61 3 9433 2211

Email: info@arpansa.gov.au
Website: www.arpansa.gov.au

Contents

Tables

Abbreviations

AGREE	Appraisal of Guidelines for Research and Evaluation
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
GRADE	Grading of Recommendations Assessment, Development and Evaluation
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
NHMRC	National Health and Medical Research Council
NT	Northern Territory
OHAT	US National Toxicology Program's Office of Health Assessment and Translation
The Guidelines	Guidelines for Managing Risks in Recreational Water (2008)
The Committee	NHMRC Recreational Water Quality Advisory Committee
UV	Ultraviolet radiation
WHO	World Health Organisation

1. Introduction

In 2008, the National Health and Medical Research Council (NHMRC) released the *Guidelines for Managing Risks from Recreational Water* (the Guidelines). The Guidelines aim to protect Australians from threats posed by the recreational use of coastal, estuarine and freshwater environments. The Guidelines are intended to be used to ensure that recreational water environments are managed as safely as possible so that as many people as possible can benefit from using the water.

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) is the Australian Government's primary authority on radiation protection and nuclear safety. ARPANSA regulates Commonwealth entities that use or produce radiation with the objective of protecting people and the environment from the harmful effects of radiation. ARPANSA undertakes research, provides services, and promotes national uniformity and the implementation of international best practice across all jurisdictions.

ARPANSA was engaged by the NHMRC to review existing evidence and guidance on the risks to human health from radiological water quality of recreational water sites. This review is to inform the development of a chapter on radiological water quality in the updated Guidelines.

The aim of this report is to assess the body of evidence and existing relevant guidelines relating to risks to human health from radiological hazards in recreational water environments.

This Evidence Review Report includes an overview of the methods used to identify and appraise the evidence, and the key findings. Details of the literature search strategies, included/excluded studies, characteristics of included studies, and risk of bias assessments are also included in this report.

1.1 Scope

The updated Guidelines will consider the public health risks associated with recreational *water quality* only. This includes human health risks from hazards that affect the quality of recreational water that people might be exposed to. The risks include those characteristics of recreational water quality, including the presence of microorganisms, cyanobacteria and algae, free-living microorganisms, chemical and radiological hazards.

The updated Guidelines are intended to be applied within the broader context of protecting public health and as such are not intended to be prescriptive given the variety of recreational water settings and climates across Australia. The inclusion of a Risk Management Framework is intended to allow for structured risk assessment and risk management planning across the wide variety of existing and emerging recreational water environments that Australian risk managers might encounter. This also includes any unique sites that are currently unregulated and may present risks to public health.

This evidence review only considers evidence on radiological hazards.

The following risks are **excluded**:

- risks from sun (including UV radiation), heat and cold and other physical hazards associated with recreational water (e.g. drowning, animal attacks)
- risks associated with exposure to foodstuffs collected from recreational water or its surroundings

- risks associated with ancillary facilities that are not part of the recreational water environment other than risks that may affect water quality (e.g. toilet facilities in adjacent areas are not considered unless these need to be managed to minimise contamination of the recreational water body)
- adverse health effects that are not caused by recreational water quality (e.g. seasickness, the 'bends')
- risks from sand/soil around recreational water bodies (unless disturbances of sand/soil affects water quality); however, the risk management framework should include assessment of these risks.

1.2 Definitions

The definitions to be applied are:

Recreational water:

Included: Any natural or artificial water bodies without a chemical disinfectant residual that might be used for recreating including coastal, estuarine and freshwater environments. Includes public, private, commercial and non-commercial recreational water sites. Includes unique unregulated sites such as wave pools, ocean- or river-fed swimming pools, artificial lagoons and water ski parks.

Excluded: Aquatic facilities using chemical disinfection including swimming pools, spas, splash parks, ornamental water sites.

Recreational water use:

Included: Any designated or undesignated activity relating to sport, pleasure and relaxation that involves whole body contact or incidental exposure (through any exposure route) to recreational water (e.g. swimming, diving, boating, fishing)

Excluded: Consuming the catch from fishing or foodstuffs collected from recreational water or its surroundings. Therapeutic uses of waters (e.g. hydrotherapy pools). Occupational exposure (noting that occupational studies may be useful to determine risk for high exposure scenarios).

Recreational water users:

Recreators or users of recreational water bodies including:

- the general public including all relevant life stages, ages and states of health other than persons that are explicitly advised to avoid such activities (e.g. for specific medical conditions)
- tourists
- specialist sporting users (e.g. athletes, anglers, kayakers, divers, surfers)
- any other groups that may have high exposures to recreational water through non-occupational exposures.

2. Evidence Review Methods

The following section details the approach that was undertaken to search for and assess the available literature within scope of this Evidence Review.

2.1 Research questions

This Evidence Review was structured around answering the specified research questions on the sub-topic of radiological quality of Australian recreational waters. The questions comprised one primary question and one secondary question. The research questions were developed and approved by the NHMRC and the NHMRC Recreational Water Quality Advisory Committee. The research questions were used as the basis for study selection.

Primary Question

Are there any risks to human health from radiation in Australian recreational waters?

Secondary Question

How are these risks monitored and managed?

2.2 Criteria for determining study eligibility

For this Evidence Review, evidence was included if it met the detailed population, exposure, comparator, and outcome (PECO) criteria in Table 1 and was published from 1963 onwards.

Table 1. Population, exposure, comparator and outcome review parameters (provided by NHMRC)

Element	Criteria

Population	- The general population
	- Specific subpopulations that might need to be considered:
	  ○ Elderly
	  ○ infants and children
	  ○ pregnant women
	  ○ First Nations peoples
	- Any groups that might be exposed more frequently as a result of inequity e.g. geographic location, socioeconomic status or lifestyle/occupation
	- Subgroups with unusual exposure patterns making them more susceptible (e.g. athletes, people or age-groups practicing energetic water-based activities) due to larger volumes of water ingested and/or inhaled, different frequency of exposure etc.

Exposure (and comparator)	- Exposure to relevant sources of radiation in recreational water present in Australia - May need to consider additional exposure scenarios e.g. surface water vs. groundwater/waste disposal/sediments near recreational water bodies that may affect water quality - All routes of exposure (oral, dermal, inhalation) compared to no exposure. Note that assumption values are different for recreational water than drinking water (i.e. accidental ingestion, frequency) and are under review by the Recreational Water Quality Advisory Committee - Include circumstances that lead to elevated exposures (e.g. sediment concentrations and exposure) - Compared to average background radiation levels in Australia. Note that some water sites in Australia (e.g. mineral springs) have higher natural sources of

	background radiation which may also be considered
Outcomes	- All relevant human health outcomes of interest
Study type	- Publicly available, peer reviewed publications are required for any public health recommendations especially guideline values or reference levels – any unpublished exposure data can be considered for background/supporting information but if included will need to seek permission to publish or report as part of a range - Existing guidance documents (international, national) - Grey literature (government or research organisation reports/papers) - Epidemiological studies where possible, environmental data for exposure levels in recreational water
Other criteria	- Inclusion criteria: o studies that provide qualitative or quantitative evidence to address the research questions - Exclusion criteria: o studies that provide data only for water bodies within a controlled area (e.g. an operating mine site). These are out of scope of the updated Guidelines o studies reporting the presence of radionuclides but not their activity or concentration in water. Natural radionuclides are present in low concentrations in most water bodies, therefore their presence, without additional information, does not provide information that assists in answering the research questions

2.3 Literature search

A literature search was conducted by ARPANSA to identify and select relevant evidence to consider for the Evidence Review. This included reviews of both peer reviewed publications and grey literature.

Searches were restricted to English-language, full text articles. Primary studies and conference abstracts/proceedings were eligible, letters and dissertations were excluded. The literature searches were conducted on 15th of September 2019 in PubMed® and Web of Science®. The start date for included literature was 1963 onwards. Further details regarding the search strategy and search dates are available in Sections 2.3.1, 2.3.2 and 2.3.3. After deduplicating records in EndNote 20, unique records were reviewed for determination of study eligibility.

In addition to the formal literature search, a targeted grey literature search was conducted using the Google search engine to source guideline values used for radiological contaminants in recreational water internationally. Further details on the grey literature search can be found in Section 2.3.4.

It is noted that some other contracted reviews to support the update to the Guidelines (e.g. chemical hazards) are being conducted using a systematic narrative review approach. To keep this Evidence Review on the risks to human health posed by radiological hazards in recreational water within project resources and timeframes, NHMRC supported a simpler, pragmatic approach that focused on transparency while attempting to undertake similar critical appraisal approaches consistent with the other reviews.

2.3.1 Search Strategy

The search strategy for the literature review was primarily developed to retrieve evidence for the primary question “Are there any risks to human health from radiation in Australian recreational waters?”.

2.3.2 Databases

The databases PubMed® and Web of Science® were searched to capture the conventional peer-reviewed published literature. The PubMed database was selected due to its open access and comprehensive database on biomedical and life sciences literature (https://pubmed.ncbi.nlm.nih.gov/). This database has over 30 million articles from 1966 to the present, with further selective articles from 1809. The Science Citation Index Expanded (SCI-EXPANDED; 1900 to present), Conference Proceedings Citations Index – Science (CPCI-S; 1990 to present and Emerging Sources Citation Index (ESCI; 2005 to present) databases were selected from the Web of Science Core Collection to conduct the literature search. These databases were selected as they were most relevant for the topic and included grey literature published as part of conference proceedings.

2.3.3 Search protocol and structure

The searches employed advanced search techniques which involved the development of a structured search that was able to capture literature based upon radiation source terms combined with both water-based recreation and health outcomes for the freshwater and marine environments. The search terms were categorised into three distinct groups:

Exposure: thorium, uranium, plutonium, radon, polonium, gamma, radiation, radionuclide, radiological, radioactive, ionising, ionizing, tailings, NORM, radioactivity, U-238, Th-232, Ra-226, Po-210, Th-228, Po-208, dose, fallout

Water bodies: river, lake, estuary, dam, reservoir, creek, waterhole, stream, spring, pond, surface water, freshwater, groundwater, foreshore, marine, island, aquatic

Location: Australia

The search terms within the ‘exposure’ and ‘water bodies’ categories were combined using the Boolean operator ‘OR’. The Boolean operator ‘AND’ was then used to combine these 3 categories. When necessary, search terms were written with a wildcard at the end to include alternate forms of the word. The final Boolean search strings can be found in Appendix 1: Radiological Quality Recreational Water Literature Search.

2.3.4 Grey Literature search

In addition to the database searches, a targeted grey literature search was conducted using the Google search engine to source guideline values used for radiological contaminants in recreational water internationally. These searches were also carried out to gather information on how radiological risks are currently managed for recreational waters in Australia.

Key national and international agencies were searched for relevant reports, including the:

- International Atomic Energy Agency (IAEA)
- World Health Organization (WHO)

- International Commission on Radiological Protection (ICRP)
- Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)
- National Health and Medical Research Council (NHMRC)

Relevant reports were collated and evaluated to determine whether there was information relevant to answering the research questions, including any guideline values that could potentially be adopted/adapted.

2.4 Study eligibility

Study eligibility was informed by the PECO criteria outlined in Table 1. All evidence selection criteria were applied in two stages: first to the titles/abstracts and then to the full publications/reports of potentially included studies. Records were excluded for the following reasons:

- not in English – full text article not in English language.
- wrong population
- wrong exposure (and comparator)
- wrong study type – not a full-text report or conference abstract (excludes protocols, editorials, letters)
- studies that provide data only for water bodies within a controlled area (e.g. an operating mine site).
- studies reporting the presence of radionuclides but not their activity or concentration in water. Natural radionuclides are present in low concentrations in most water bodies, therefore their presence, without additional information, does not provide information that assists in answering the research questions.

2.5 Evidence Review Process

The Evidence Review process to answer the research questions included two components:

- a literature search and review of selected studies
- a targeted review of recommendations, existing guidelines and guidance from a selected number of national and international organisations responsible for radiological protection.

The literature search was conducted on the 15th of September 2019. Retrieved articles from the database searches were uploaded to EndNote 20 for screening. Prior to screening, duplicates were removed as well as articles not in English using EndNote functions. The review considered papers and reports published from 1963 onwards and search results were restricted to English language publications only.

2.5.1 Screening Methods

All studies that met the PECO eligibility criteria were processed by a two-stage screening process to select papers that would proceed to full-text review. Articles were screened in three stages: title, abstract and full text. Title and abstract screening was undertaken by a single reviewer. Full text screening was undertaken by two reviewers. The publications were screened against the review parameters in Table 1, as well as relevance to answering the primary and secondary research questions.

Step 1: Assessment of relevance to answer the primary or secondary questions by examination of the publication title. In many cases papers were clearly not relevant to the review questions and were excluded.

Step 2: Additional review of the title in conjunction with the abstract for relevance to the primary and secondary questions.

Step 3: Full text review of studies for relevance to the primary and secondary questions.

2.6 Evidence appraisal

The NHMRC project team completed critical appraisal of relevant included primary studies and guidelines identified by ARPANSA, the findings of which are included in this report. Existing guideline publications were assessed by the NHMRC project team against an Assessment Tool developed specifically for water projects. Included primary studies were assessed for risk of bias and certainty where possible using existing tools and frameworks used in similar contracted reviews (e.g. OHAT risk of bias tool - OHAT, 2019).

Data relevant to answering the research questions was extracted by ARPANSA from included publications and summarised for consideration by NHMRC and the NHMRC Recreational Water Quality Advisory Committee.

2.6.1 Evidence appraisal methods

The included primary studies were assessed for risk of bias using an adaptation of the OHAT risk of bias tool (OHAT, 2019). Existing guidance or review reports such as those found in the grey literature search were appraised using an Assessment Tool provided by NHMRC based on common domains for assessing guidelines and systematic reviews such as the Appraisal of Guidelines for Research and Evaluation (AGREE) tool (Brouwers et al., 2016; AGREE Next Steps Consortium, 2017). The certainty of the body of evidence was assessed where appropriate.

At least one reviewer performed an assessment on each included study. All assessments were checked internally by the NHMRC project team.

3. Results

3.1 Literature search results

The results of the searches in PubMed® and Web of Science® databases and the records identified from other sources were combined to produce 3,340 studies. After the removal of 213 duplicates or papers not published in English, a total of 3,127 records were screened in a two-stage process to select eligible papers to be included in the review. The process undertaken for the search and selection of studies for this review is presented in Figure 1. This is modified from the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) flow diagram (Page et al. 2021).

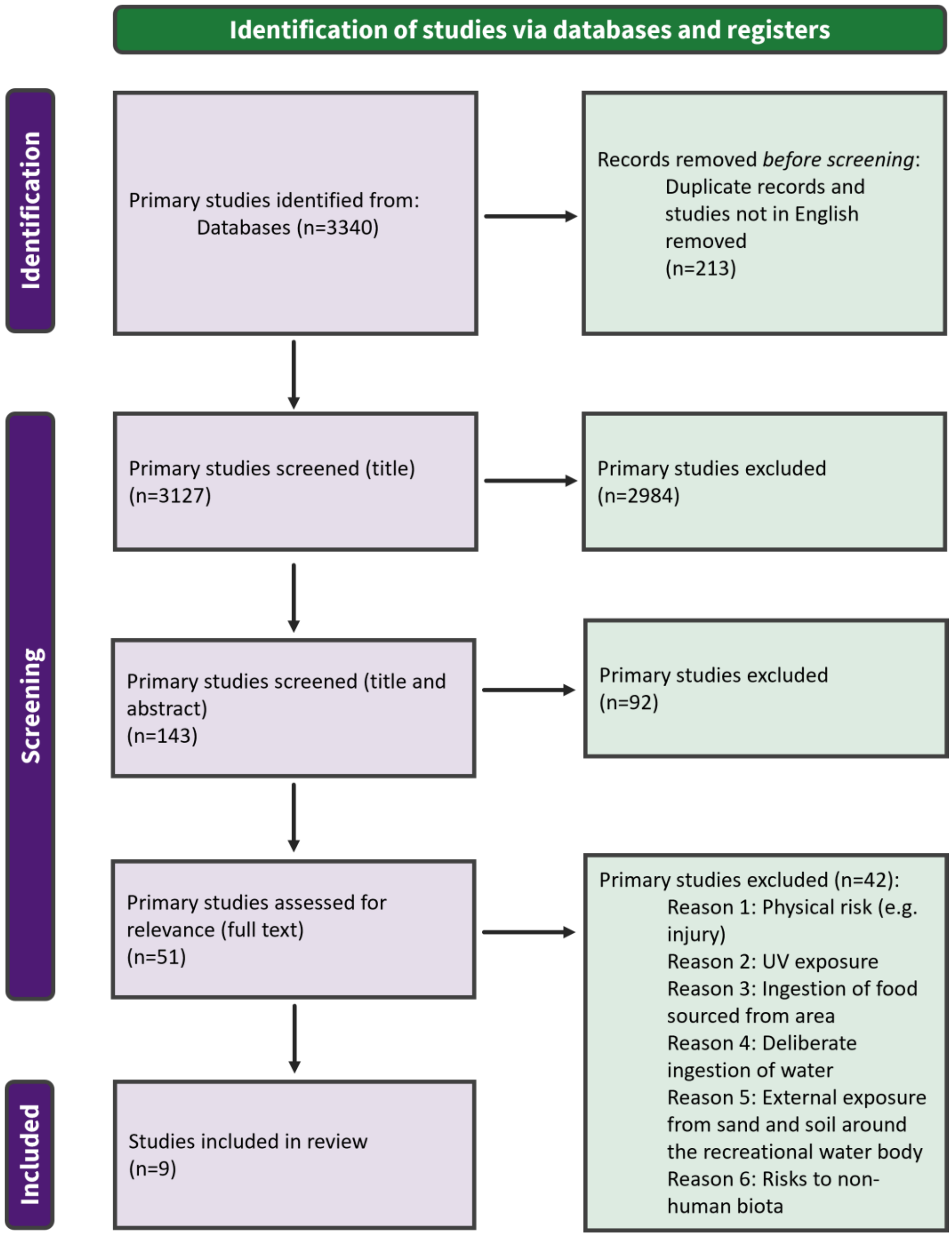

Figure 1 Process undertaken for the search and selection of primary studies

Of the 3127 records identified in the literature search, 143 records were progressed following title screening. Following abstract screening, 51 records were assessed by full-text review for relevance to answering the primary and secondary questions. The full-text review identified nine records that were relevant to answering the research questions. These records are summarised in Table 2. Many papers that initially appeared to be potentially relevant to the topic in stages 1 and 2 of the screening process were later rejected in stage 3. This was due either to not containing data or information relevant to addressing the research questions, or only providing data obtained from restricted areas that are not accessible for recreational purposes such as operational mine sites. A list of excluded studies following full text screening is provided in Appendix 2: Excluded studies following full text screening.

A search for relevant grey literature from international and national agencies did not identify any guideline values specifically designed for radiological contaminants in recreational waters for adoption/adaption. The IAEA and ARPANSA classify recreational water as an existing exposure situation for radiation protection purposes, therefore generic recommendations and guidance for existing exposure situations are considered applicable in this case. Results from the grey literature search and screening are summarised in Appendix 3.

3.2 Data extraction and synthesis

The Evidence Review identified nine studies containing information relevant to answering the primary question "Are there any risks to human health from radiation in Australian recreational waters?". Of these papers, five discussed the impacts of uranium mining on offsite water bodies in the Alligator Rivers Region (ARR) of the Northern Territory (NT), two addressed the impacts of uranium mining on offsite water bodies in other locations, one provided measurement data for uranium, thorium and radon levels at a natural hot spring, and one provided data and discussion of the potential for radiological contaminants in treated and processed waste water. The nine studies are summarised in Table 2. Summary of included studies and Table 4. Key characteristics and assessment of included studies

The grey literature search identified six sources with potential relevance to the research questions (see Table 3. Summary of included Grey Literature). These included the:

- International Atomic Energy Agency (IAEA)'s General Safety Standards Part 3 (GSR Part-3)
- World Health Organization Guidelines on recreational water quality: Volume 1 coastal and fresh waters (2021)
- Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)'s Guide for Radiation Protection in Existing Exposure Situations (ARPANSA 2017) (Existing Exposure Guide)
- Alligator Rivers Region, Northern Territory Supervising Scientist's environmental monitoring publications
- Department of Industry, Science, Energy and Resources (Commonwealth) report on the rehabilitation of former nuclear test sites at Emu and Maralinga and
- Department of Parks and Wildlife (WA) information on the Montebello Island

Table 2. Summary of included studies

Title	Summary	How does this paper inform the primary and/or secondary questions?
Abdelouas, A. (2006). "Uranium mill tailings: Geochemistry, mineralogy, and environmental impact." Elements 2(6): 335-341.	Discusses environmental impacts of uranium mining. Contamination of ground and surface waters from tailings is known to occur, particularly for in-situ leach mining and for past-practices where tailings have not been appropriately managed. Internationally, estimated additional radiation dose in the vicinity of uranium mines has been estimated to range from 1-6 mSv per annum. This dose is from all sources including radon inhalation, external gamma exposure from soil/rock/sediment and surface water contamination. Activity concentrations and doses specifically from surface water contamination are not provided or discussed.	Indicates that radiological contamination of surface water in the vicinity of uranium mine sites is possible. Does not provide data or evidence to quantify the health risk from such contamination.
Brugger, J., N. Long, D. C. McPhail and I. Plimer (2005). "An active amagmatic hydrothermal system: The Paralana hot springs, Northern Flinders Ranges, South Australia." Chemical Geology 222(1-2): 35-64.	Elevated U and Ra-222 levels have been measured at areas in the Paralana hot springs (PHS), exceeding 10,000 Bq/m^3 radon at one pool. The PHS offer a permanent water source in an arid environment and are culturally important to local Aboriginal communities.	The measured Ra-222 levels exceed the Australia reference level for radon exposure. It is likely that only a small number of individuals would be exposed. It is not clear whether exposure from radon at PHS is within the scope of the updated Guidelines as: - the exposure is due to a natural source of background radiation (the comparator) - the exposure is due to inhalation of radon gas (noting that external exposure to nearby soil, sand or rock is excluded from consideration in the updated Guidelines. It is expected that such exposures would be considered within the wider risk management framework for the site.)
Ferguson, B. and G. M. Mudd (2011). "Water Quality, Water Management and the Ranger Uranium Project: Guidelines, Trends and Issues." Water Air and Soil Pollution 217(1-4): 347-363.	A review of historical data indicates that there is potential for periods of increased uranium (U) levels in waters offsite (Ranger U-mine, NT) compared to what is observed from natural variability, but that these increased levels are below guideline values derived based on ecotoxicological testing.	For this water body, radiological contamination (offsite) is within guideline levels established for the Ranger uranium mine based on site-specific data radiological risk assessment.

Frostick, A., A. Bollhöfer, D. Parry, N. Munksgaard and K. Evans (2008). "Radioactive and radiogenic isotopes in sediments from Cooper Creek, Western Arnhem Land." J Environ Radioact 99(3): 468-482.	This study found no indication that the radiogenic erosion products found on the mine site (Nabarlek, NT) at present have significantly contaminated sediments further downstream of Cooper Creek. The study does not include water samples, only soil and sediment.	While water samples were not included in the study, the lack of contaminated sediment and soil indicates that there is unlikely to be surface water contamination at a level that would impact human health.
Hancock, G. R., M. K. Grabham, P. Martin, K. G. Evans and A. Bollhöfer (2006). "A methodology for the assessment of rehabilitation success of post mining landscapes--sediment and radionuclide transport at the former Nabarlek uranium mine, Northern Territory, Australia." Sci Total Environ 354(2-3): 103-119.	The objectives of this research were to quantify the gross erosion and radionuclide flux from the rehabilitated surface of the Nabarlek mine site (NT), and to estimate the degree to which sediment loads and radionuclide concentrations in the waters draining the mine site. Sediment concentration in Cooper Creek, which drains the site, was found to be within the NHMRC Australian Drinking Water Guidelines for fresh water: however, sediment concentrations in tributaries were found to exceed recommended levels.	While water samples were not included in the study, the presence of contaminated sediment in excess of guideline values indicates that there is a possibility of surface water contamination that may need investigation if the water body were to be used for recreational purposes.
Kleinschmidt, R. and R. Akber (2008). "Naturally occurring radionuclides in materials derived from urban water treatment plants in southeast Queensland, Australia." J Environ Radioact 99(4): 607-620.	Radioactivity concentrations of U-238, Th-232, Ra-226, Rn-222, and Po-210 in water, sourced from both surface water catchments and groundwater resources were examined both pre- and post-treatment under typical water treatment operations. The results indicate that, under current water resource exploitation programs, reuse or disposal of the treatment wastes from large scale urban water treatment plants in Australia do not pose a significant radiological risk.	Under current water resource exploitation programs, there is not a significant radiological risk from the reuse or disposal of treatment wastes from large scale urban water treatment plants in Australia.
Lottermoser, B. G. and P. M. Ashley (2005). "Tailings dam seepage at the rehabilitated Mary Kathleen uranium mine, Australia." Journal of Geochemical Exploration 85(3): 119-137 .	This study reports on the seepage of metals, metalloids and radionuclides from the Mary Kathleen uranium mill tailings repository. While the release of contaminant loads from the waste repository through seepage is insignificant (e.g. similar to 5 kg of U per year), surface waters downstream of the tailings impoundment possess TDS, U and SO4 concentrations that exceed Australian water quality guideline values in livestock drinking water. Thus, in areas with a semi-arid climate, even insignificant load releases of contaminants from capped tailings repositories can still cause the deterioration of water quality in ephemeral creek systems.	In areas with a semi-arid climate, even insignificant load releases of contaminants from capped tailings repositories can still cause the deterioration of water quality in ephemeral creek systems.
Mudd, G. M. and J. Patterson (2010). "Continuing pollution from the Rum Jungle U-Cu project: a critical evaluation of environmental monitoring	The former Rum Jungle mine remains a polluting site – as evidenced by the range of available monitoring data and recent site inspections. Two examples include polluted groundwater which was	This paper does not provide water concentrations or activities for radionuclides but does indicate that there is a potential contamination problem near some

and rehabilitation." Environ Pollut 158(5): 1252-1260.	excluded from rehabilitation and the poor design, construction and/or performance of engineered soil covers – both leading to increasing acid drainage impacts on the Finniss River. The radiological characterisation and assessment of the site remains poor, despite clear evidence of extreme U concentrations in seepage from White's WRD and accumulated U in Finniss River sediments.	former/legacy mine sites.
van Dam, R. A., C. L. Humphrey and P. Martin (2002). "Mining in the Alligator Rivers Region, northern Australia: assessing potential and actual effects on ecosystem and human health." Toxicology 181-182: 505-515.	In the case of uranium mining and milling, the risks to human health from uranium include both the risk of radiation exposure and non-radiological risk associated with uranium intake. For the critical group (identified as Aboriginal people living downstream of the Ranger mine), the major dose contribution is from ingestion of bush foods, followed by toxicity effects of drinking billabong water (both out of scope the updated Guidelines). For radiological protection of humans, limits for individual radionuclide concentrations cannot be derived because the dose must be summed over all radionuclides and all pathways before comparison with the dose limits. Rather, concentration measurements for the waste water are used in conjunction with a dose model to ensure prior to the release that the limit will not be exceeded. In addition, a monitoring regime targeting the most important radionuclides and food items is used to check that compliance has been achieved.	Discusses two important points: 1. toxicity effects of ingesting uranium are generally more limiting than radiological effects for the same exposure 2. the accepted best-practice approach for radiological protection is to sum the dose received over all pathways rather than setting a limit for a specific pathway (i.e. water concentrations would usually be considered within a wider risk management framework)

Table 3. Summary of included Grey Literature

Organisation	Relevant Documents	Key findings
European Commission, Food And Agriculture Organisation Of The United Nations, International Atomic Energy Agency (IAEA)	*General Safety Standards Part 3* (GSR Part-3), co-sponsored by the European Commission (EC/Euratom), FAO, ILO, OECD/NEA, PAHO, UNEP and WHO	Includes requirements for radiation protection in existing exposure situations. Recreational waters are considered an existing exposure situation for radiation protection purposes.
World Health Organization (WHO)	*Guidelines on recreational water quality: Volume 1 coastal and fresh waters* (2021)	No guidance for radiological water quality
International Commission on Radiological Protection (ICRP)	N/A	No guidance for radiological water quality related to recreational water use
Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)	*Guide for Radiation Protection in Existing Exposure Situations* (ARPANSA 2017) (Existing Exposure Guide)	ARPANSA, jointly with state and territory regulators in the Radiation Health Committee (RHC), has developed this Guide based on the 'requirements' relating to existing exposure situations described in the Safety Requirements of GSR Part-3 (IAEA). The Guide establishes a framework in Australia for the protection of occupationally exposed persons, the public and the environment in existing exposure situations, which includes exposure from recreational waters. This guide applies a risk-based approach when considering the application, justification and optimisation of existing exposure strategies and remedial actions.
Alligator Rivers Region, Northern Territory /Supervising Scientist	Supervising Scientist publications - DCCEEW	The Supervising Scientist publishes the results of environmental monitoring and research by staff and external authors into the impact of uranium mining on the environment of the Alligator Rivers Region of the Northern Territory and research on the sustainable use and environment protection of tropical rivers and their associated wetlands, and also its work on supervision and assessment of uranium mining activities. Included in these reports are various recommendations for site-specific guideline levels for radionuclides in offsite waters. These values have been established based on site-

		specific conditions and criteria.
Department of Industry, Science, Energy and Resources (Commonwealth)	Rehabilitation of former nuclear test sites at Emu and Maralinga (Australia) 2013 | Department of Industry, Science, Energy and Resources	Report on the rehabilitation of former nuclear test sites in South Australia. No evidence to suggest that there is a radiological risk from recreational water use in these areas.
Department of Parks and Wildlife (WA)	Montebello Islands | Explore Parks WA | Parks and Wildlife Service (dpaw.wa.gov.au)	The islands are within a protected Marine Park. Restrictions are in place to protect the islands wildlife and ecosystems, as well as to minimise radiation exposure to people.

3.3 Evidence appraisal

3.3.1 Risk of bias

The nine included publications that spanned environmental testing, environmental monitoring and modelling studies were individually evaluated for risk of bias using the US National Toxicology Program's Office of Health Assessment and Translation (OHAT) risk of bias tool (OHAT, 2015). The OHAT tool provides a way to evaluate individual study risk of bias or internal validity – the assessment of whether the design and conduct of a study compromised the credibility of the link between exposure and outcome. Applying the OHAT risk-of-bias rating tool provides a way to evaluate risk of bias in human and non-human animal studies. Aspects such as the study design, conduct, and reporting required were assessed to reach an overall risk-of-bias rating. An adaptation of the Appraisal of Guidelines for Research and Evaluation (AGREE) tool was used to evaluate the risk of bias in one review article, Abdelouas 2006. A summary of the risk of bias assessments for the nine included publications is provided in Table 4, with the full risk of bias assessments for included studies and existing reviews/guidance documents provided in Appendix 3: Risk or bias assessments for included radiological risk studies and reviews

3.3.2 Certainty of evidence

A certainty of evidence rating can aid in interpretation of included studies. It indicates how confident we are in the evidence that supports answering the research question. The Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach is a way to assess the certainty of a body of evidence and is considered best practice by many international organisations that develop clinical guidelines. GRADE assessment provides a structured way to consider key factors that may increase or decrease our confidence in the synthesised findings of a body of evidence including the risk of bias; the precision of the effect estimates; the consistency of the individual study results across the body of evidence; how directly the evidence answers the question of interest and the risk of publication or reporting biases.

Given the heterogeneity of the studies in this Evidence Review and the diverse measured outcomes of the nine included studies, an assessment of certainty across the body of evidence by GRADE was not considered appropriate as the evidence streams could not be grouped into similar groups and outcomes. However, the NHMRC project team was able to use a systematic approach based on the OHAT tool criteria to make a broad assessment of the certainty of the included studies with the information that was reported in the studies. An assessment of the certainty of evidence was undertaken (Appendix 4: Confidence ratings for included radiological risk papers), the result of which are summarised in Table 4. Overall, there was either low or very low certainty in the ability of the evidence to answer the research questions posed a priori. A low certainty of evidence rating means we have only low confidence that the evidence supports any resulting recommendation. A very low rating equates to any estimate of effect being very uncertain.

Factors that contributed to the low to very low certainty ratings of the evidence retrieved in this review included:

- the risk of bias ratings obtained using the OHAT assessment tool (see Table 4)

- the results of the included publications were not reported via an outcome that was directly relevant to the research question
- the studies were single case studies or observational studies, or had small sample sizes led to an inability to measure precision (noting that all observational studies begin with a *low* rating).
- monitoring studies do not lend themselves to a magnitude of effect or dose response.

Despite the low to very low certainty ratings, the studies included in this Evidence Review do represent the best available evidence from Australian sites in support of the research question and can still be used as background information.

Table 4. Key characteristics and assessment of included studies

Study ID	Study Type	Topic	Country; Setting	Risk of bias[a]	Reasons for risk of bias rating	Certainty rating[b]
Abdelouas 2006	Mixed review	Worldwide Uranium Mill Tailings and their impact.	Worldwide	Definitely high	This is a general review article that discusses worldwide uranium mill tailings and their impact. The paper provides a summary of previous findings without reporting methods that demonstrate a critical analysis of the papers and reports under consideration or explanation of any data analysis that led to the review conclusions.	Very Low
Brugger et al., 2005	Environmental testing study (Observational environmental study)	Hydrothermal mineralisation in the Paralana hot springs, Northern Flinders Ranges, South Australia.	Australia; Northern Flinders Ranges, South Australia	Probably High	There were concerns about missing outcome data (some samples were discarded due to contamination) and some concerns about environmental contamination potentially affecting results. The paper also notes that the other water sources may not represent subsurface conditions because the discharge rates of the springs is unknown and the bore and wells could not be purged.	Very Low
Ferguson et al., 2011	Radiological monitoring study (Observational study)	Water Management downstream from the Ranger Uranium Project	Australia; Alligator Rivers Region, Northern Territory (NT)	Probably High	There were some concerns about detection bias and selective reporting bias (e.g. data collected over the years has been adjusted to align with weeks since the beginning of the wet season to make them comparable and data is affected by changes to sampling processes and work practice changes over time).	Very Low
Frostick et al., 2008	Environmental modelling study (Observational environmental study)	Radioactive and radiogenic isotopes in sediments and soils surrounding the former Nabarlek uranium mine (NT).	Australia; Former Nabarlek uranium mine and Cooper Creek, West Arnhem Land, NT	Probably Low	Although there were questions of repeatability, overall, there is a probable low risk of bias as there is indirect evidence that sites were similar across the different exposure types (i.e. location in relation to mine); however, there may be variations in the characteristics of core sample sites. There was no missing outcome data and site selection and sample	Low

					selection was appropriate.	
Hancock et al., 2006	Environmental testing study (Observational environmental study)	Methodology for assessment of the environmental impact (including water quality) and long-term behaviour of post-mining landforms of the former Nabarlek uranium mine (NT).	Australia; Former Nabarlek uranium mine (NT)	Probably High	There were serious concerns about confounding in this study (the sediment concentration predictions did not consider the presence of sediment containment ponds which are present in some of the streams and may result in a discharge of sediment if they are breached, and the impact of feral animals such as pigs and horses on the site were not taken into consideration. Initial erosion calculations did not take into account site specific field data.	Very Low
Kleinschmidt et al., 2008	Environmental testing study (Observational environmental study)	An assessment of radiologically enhanced residual materials generated during treatment of domestic water supplies.	Australia; Urban water treatment plants in southeast Queensland	Probably High	There were some concerns about detection bias (repeat sampling or sampling of similar environments was not conducted. This means that for some treatment methods an individual result is used as the assumed value for that treatment type), and there were some concerns about confounding. The study did not provide sufficient information regarding occupational co-exposures for the modelling conducted in the study.	Very Low
Lottermoser et al., 2005	Environmental testing study (Observational environmental study)	This study reports on the seepage of metals, metalloids and radionuclides from the Mary Kathleen uranium mill tailings repository.	Australia; The Mary Kathleen mine, located 60 km east of Mt. Isa, northwest Queensland	Probably Low	The paper was assessed as a generally low risk of bias; however, there were some concerns about selective reporting bias (e.g. the limited number of water samples analysed does not allow for an evaluation of long term trends developing in ground and surface waters).	Low
Mudd, et al., 2010	Radiological monitoring study (Observational study)	Environmental monitoring and rehabilitation of the former Rum Jungle uranium-copper project, (NT).	Australia; The former Rum Jungle mine site, located 100km south of Darwin	Probably High	There were concerns about exclusion bias as the authors noted that collection of some samples (e.g. groundwater) has not been undertaken continuously over the period of the environmental monitoring program so some datasets and parameters are incomplete. Historical data was presented and evaluated – noting that there was	Very Low

				Probably High	incomplete data so authors unable to accurately account for all pollutants.	
Van Dam et al., 2002	Radiological monitoring study (Observational study)	Overview of issues related to surface water contamination arising from uranium mining activities in the Alligator Rivers Region (ARR) of northern Australia	Australia; Alligator Rivers Region, Northern Territory (NT)	Probably High	There were concerns about missing outcome data (System monitoring data is not presented for all activities) and concerns about selective reporting bias (data is referenced for a range of monitoring activities, but primary data is not provided).	Very Low

a Risk of bias determined by NHMRC based on the OHAT risk of bias tool methods (OHAT, 2015)

b Certainty rating determined by NHMRC based on the OHAT risk of bias tool methods (OHAT, 2015)

Table 5: Risk of bias assessment of included studies

Study	Selection Bias	Confounding Bias	Attrition/Exclusion Bias	Detection Bias: Exposure characterisation	Detection Bias: Outcome assessment	Detection Bias: Sample characterisation	Selective Reporting Bias	Other Sources of Bias	Overall risk of bias rating
Brugger et al., 2005	+	-	-	+	-	N/A	-	+	-
Ferguson et al., 2011	-	-	+	-	-	N/A	-	-	-
Frostick et al., 2008	+	-	+	N/A	-	+	+	+	+
Hancock et al., 2006	-	--	-	-	+	N/A	+	-	-
Kleinschmidt et al., 2008	-	-	+	-	+	N/A	+	N/A	-
Lottermoser et al., 2005	+	+	+	+	+	N/A	-	N/A	+
Mudd, et al., 2010	-	-	-	+	-	N/A	-	N/A	-
van Dam et al., 2002	+	-	-	+	-	N/A	-	N/A	-

Risk of bias rating key:

Definitely low risk of bias (++)	++
Probably low risk of bias (+)	+
Probably high risk of bias (-)	-
Definitely high risk of bias (--)	--

4. Discussion

4.1 Primary Research Question

Are there any risks to human health from radiation in Australian recreational waters?

The literature search and subsequent screening identified nine studies containing information relevant to answering the primary question. The studies were appraised for risk of bias and certainty (See Table 4 and Appendix 3 and 4). Although the quality of these papers is considered low to very low quality as they are predominantly case studies or observational studies, they are relevant to the Australian context and represent the best available evidence to answer the research questions. Of these papers, five discussed the impacts of uranium mining on offsite water bodies in the Alligator Rivers Region (ARR) of the Northern Territory (NT), two addressed the impacts of uranium mining on offsite water bodies in other locations, one provided measurement data for uranium, thorium and radon levels at a natural hot spring, and one provided data and discussion of the potential for radiological contaminants in treated and processed waste water. Results are summarised in Table 2.

To answer the primary research question two points need to be considered:

1. Is there potential for recreational waters in Australia to contain radiological contaminants at levels in excess of natural background radiation (the comparator)?
2. If yes to 1, is this contamination at a level that is a risk to human health?

The small number of published studies identified in this review, and the results of these studies, suggests that there are very few recreational water bodies in Australia that are likely to be contaminated by radionuclides at levels in excess of those that occur naturally in the environment. Five of the studies provided qualitative evidence indicating that radiological contamination of surface waters in excess of background levels is possible in the vicinity of current and former uranium mines. However, no evidence was provided that indicated this contamination was at a level that would be considered harmful to human health from the exposure pathways that are within the scope of the Guidelines.

The water bodies identified in the studies that have potential for radiological exposure are of the type that are often already known to local and state/territory governments, and indeed all of the sites identified within this review are known to local, state/territory and federal government agencies, and risk mitigation strategies are already established for these sites. This suggests that intelligence on current and past activities in the area and upstream is useful for indicating the likely presence of contaminated sediments and water bodies. Based on the results of the literature review, activities and geographic features that may indicate the potential for radiological contamination of surface water include:

- ***Uranium mining***

  Results from Abdelouas (2006) indicate that radiological contamination of surface water in the vicinity of a uranium mine site is possible; however, no data was provided to quantify the potential dose from the radionuclides detected in the water.

  Ferguson and Mudd (2011) found that while historical data indicates there is potential for periods of increased uranium levels in waters in the vicinity of the Ranger uranium mine (Northern Territory), current data shows that offsite radiological contamination is within the site-specific guideline levels that have been established by the regulator for the region. There is also evidence (Hancock et al. 2006; Lottermoser, B. G. and P. M. Ashley (2005); Mudd, G. M. and J. Patterson (2010) indicating the potential for contaminated sediments to accumulate in offsite water bodies. However, there is no evidence to suggest that this contamination leads to a radiation dose of concern due to exposure from water in recreational scenarios. As shown by van Dam et al. (2002), for the critical group (identified as Aboriginal people living downstream of the Ranger mine), the major dose contribution is from ingestion of bush foods, followed by toxicity effects of drinking billabong water. Both of these exposure pathways are outside the scope of the updated Guidelines.

It is noted that regulators of uranium mines in Australia would usually require routine monitoring for heavy metals, including uranium, and other toxic substances. Results of such monitoring may indicate the potential for radiological contamination.

- ***Waste water***

Kleinschmidt and Akber (2008) examined radioactivity concentrations of U-238, Th-232, Ra-226, Rn-222, and Po-210 in water, sourced from both surface water catchments and groundwater resources both pre- and post-treatment under typical water treatment operations. The results indicate that, under current water resource exploitation programs, reuse or disposal of the treatment wastes from large scale urban water treatment plants in Australia do not pose a significant radiological risk.

- ***Hot springs***

Mineral and thermal springs may contain increased concentrations of naturally occurring radionuclides. In most cases these sites do not lead to exposures of concern; however, undertaking recreational activities at these sites may result in elevated exposures due to inhalation of radon and intentional ingestion of mineral water. Brugger et al. (2005) measured radon levels at the Paralana hot springs in South Australia that exceeded 10,000 Bq/m^3, which exceeds the Australian reference level for radon exposure. These hot springs offer a permanent water source in an arid environment and are culturally important to local Aboriginal communities.

It is not clear to the reviewers whether exposure from radon at hot springs is within the scope of the updated Guidelines as the exposure is due to a natural source of background radiation (the comparator). Regardless, it is expected that such exposures would be considered within the wider risk management framework for the site.

- ***Former nuclear test sites***

In the 1950s and 1960s nuclear weapons testing took place in South Australia (Maralinga and Emu Fields) and Western Australia (Monte Bello Islands). The levels of radiological contamination in these areas are well studied; however, data for radionuclide concentrations in water at these sites did not appear in the literature search. For Maralinga and Emu Fields this is because there are no contaminated water bodies used for recreation in the vicinity of the test sites. Some access restrictions remain in place at the former test site at Maralinga and the site is managed by the South Australian Government. The Monte Bello islands, a group of remote islands off the Pilbara coast of Western Australia, are now a protected Marine Park. Restrictions are in place to protect the islands wildlife and ecosystems. There are access restrictions for 2 islands where radiological surveys have identified areas of elevated plutonium levels in the soil, sea sediments, beach sands and biological tissues of wildlife. Current access restrictions are considered sufficient to protect recreational users from health impacts of radiological contamination.

In summary, the evidence review does not provide strong evidence to suggest that radiological contaminants are likely to pose a risk to human health due to recreational water use in Australia. However, there are a small number of activities that may lead to an increased risk of radiological contamination of surface waters and may pose environmental effects.

4.2 Secondary Research Question

How are these risks currently monitored and managed?

The usual practice when evaluating the radiological risk to people and the environment is to sum the radiation dose across all radionuclides and exposure pathways, for a range of plausible exposure scenarios. This approach is consistent with the approach described in the draft risk management framework proposed for inclusion in the updated Guidelines. In most cases, radiation exposures from the pathways within the scope of the revised Guidelines (i.e. immersion in water, accidental ingestion) are not as high as the exposures from pathways that are out of scope of this review and the updated Guidelines (e.g. external exposure from soil, rock and sediment, deliberate ingestion of seafoods, mineral waters and bush foods, inhalation of dust or radon).

For radiation protection purposes, radiation exposure due to recreational water use is classified as an existing exposure situation by both the International Atomic Energy Agency (IAEA) and the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). **Currently there are no guidelines specifically derived for radiological water quality for recreational water use, either in the current NHMRC Guidelines (2008) or the recently revised WHO Guidelines (2021)** (see Table 3 for details).

These risks are currently managed under the framework outlined in the Guide for Radiation Protection in Existing Exposure Situations (ARPANSA 2017). ARPANSA, jointly with state and territory regulators in the Radiation Health Committee (RHC), has developed this Guide based on the 'requirements' relating to existing exposure situations described in the Safety Requirements of the International Atomic Energy Agency (IAEA) GSR Part-3. This guide applies a risk-based approach when considering the application, justification and optimisation of existing exposure strategies and remedial actions, and includes guidance on identifying, evaluating and managing radiological risks in all existing exposure situations.

4.3 Risks to human health from radiological contaminants in recreational waters in Australia

The available evidence suggests that the risk to human health from exposure to radiological contaminants in recreational waters in Australia is very low. There are very few recreational water bodies likely to contain radiological contaminants in excess of those that occur naturally in the environment. These water bodies are typically in the vicinity (or catchment area) of current or former mine sites. These sites are known to regulatory bodies and fall under the existing regulatory framework for radiation protection.

There may be recreational areas where the overall radiological risk is high enough to consider the use of management options to reduce exposure; however, in these cases the radiological risk is likely to be highest from exposure pathways considered to be outside the scope of the updated Guidelines, for example, external gamma exposure from soil and sand, or deliberate ingestion of contaminated seafoods and bush foods.

The inclusion of a Risk Management Framework in the updated Guidelines will allow for structured risk assessment and risk management planning across the wide variety of existing and emerging recreational water environments that Australian risk managers might encounter. This also includes any unique sites that are currently unregulated and may present risks to public health. It is suggested that this approach is best suited to addressing radiological hazards in recreational water environments. This approach is broadly consistent with that outlined in the Guide for Radiation Protection in Existing Exposure Situations (ARPANSA 2017).

Based on the literature review findings and international guidance, there are three potential options for a radiological water quality guideline for recreational waters that could be considered. The potential guideline options are:

1. No guideline value (retain the status quo)
    - If a situation occurs where there is potential for radiological contamination of recreational waters the recommendation is to follow the guidance in the *Guide for Radiation Protection in Existing Exposure Situations* (2017) (Existing Exposure Guide).
2. A guideline value/reference level of 10 mSv/a above natural background levels
    - This is the reference level recommended as an appropriate 'intermediate' reference level for remediation of contaminated sites. This is considered to be a reasonable generic reference level. Following risk assessment, a different, site-specific reference level may be selected.
3. A guideline value/reference level of 1 mSv/a above natural background levels
    - This is the reference level chosen for exposure to drinking water in Australia. It is the lowest reference level that should be set for an existing exposure situation.

The potential impacts of each guideline option should be considered by NHMRC with advice from the Recreational Water Quality Advisory Committee as part of the decision-making process.

5. Conclusions

This Evidence Review included nine studies with relevance to Australia, predominantly case series and observational studies, spanning environmental testing, monitoring and modelling. Five discussed the impacts of uranium mining on offsite water bodies in the Alligator Rivers Region (ARR) of the Northern Territory (NT), two addressed the impacts of uranium mining on offsite water bodies in other locations, one provided measurement data for uranium, thorium and radon levels at a natural hot spring, and one provided data and discussion of the potential for radiological contaminants in treated and processed waste water. The search for grey literature revealed six sources of information relevant to the research question posed.

The small number of published studies identified in this review, and the results of these studies, suggests that there are very few recreational water bodies in Australia that are likely to be contaminated by radionuclides at levels in excess of those that occur naturally in the environment.

In particular, the studies indicated that:

- although very few recreational water bodies likely to contain radiological contaminants in excess of those that occur naturally in the environment, contamination can be found in the vicinity (or catchment area) of current or former mine sites. These sites are known to regulatory bodies and fall under the existing regulatory framework for radiation protection.

- under current water resource exploitation programs, reuse or disposal of the treatment wastes from large scale urban water treatment plants in Australia do not pose a significant radiological risk.
- there is potential for contaminated sediments to accumulate in offsite water bodies; however, there is no evidence to suggest that this contamination leads to a radiation dose of concern due to exposure from water in recreational scenarios.

The water bodies identified in the studies included in this Evidence Review that have potential for radiological exposure are of the type that are often already known to local authorities, and risk mitigation strategies are already established for these sites.

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Appendix 1: Radiological Quality Recreational Water Literature Search

PubMed Search All Fields

Search #1 Water bodies: 1,528,335 articles retrieved

((((((((((((((((River) OR (lake)) OR (estuary)) OR (dam)) OR (reservoir)) OR (creek)) OR (waterhole)) OR (stream)) OR (spring)) OR (pond)) OR (surface water)) OR (freshwater)) OR (groundwater)) OR (foreshore)) OR (marine)) OR (island)) OR (aquatic)

Translations

River: "river's"[All Fields] OR "rivers"[MeSH Terms] OR "rivers"[All Fields] OR "river"[All Fields]

lake: "lakes"[MeSH Terms] OR "lakes"[All Fields] OR "lake"[All Fields]

estuary: "estuarial"[All Fields] OR "estuaries"[MeSH Terms] OR "estuaries"[All Fields] OR "estuary"[All Fields] OR "estuary's"[All Fields]

reservoir: "reservoir"[All Fields] OR "reservoir's"[All Fields] OR "reservoirs"[All Fields]

creek: "creek"[All Fields] OR "creek's"[All Fields] OR "creeks"[All Fields]

waterhole: "waterhole"[All Fields] OR "waterholes"[All Fields]

stream: "rivers"[MeSH Terms] OR "rivers"[All Fields] OR "stream"[All Fields] OR "streams"[All Fields] OR "stream's"[All Fields]

spring: "natural springs"[MeSH Terms] OR ("natural"[All Fields] AND "springs"[All Fields]) OR "natural springs"[All Fields] OR "springs"[All Fields] OR "spring"[All Fields] OR "spring's"[All Fields] OR "springness"[All Fields]

pond: "ponds"[MeSH Terms] OR "ponds"[All Fields] OR "pond"[All Fields]

surface: "surface"[All Fields] OR "surface's"[All Fields] OR "surfaced"[All Fields] OR "surfaces"[All Fields] OR "surfacing"[All Fields] OR "surfacings"[All Fields]

water: "water"[MeSH Terms] OR "water"[All Fields] OR "drinking water"[MeSH Terms] OR ("drinking"[All Fields] AND "water"[All Fields]) OR "drinking water"[All Fields] OR "watering"[All Fields] OR "waters"[All Fields] OR "water's"[All Fields] OR "watered"[All Fields] OR "waterer"[All Fields] OR "waterers"[All Fields] OR "waterings"[All Fields]

freshwater: "fresh water"[MeSH Terms] OR ("fresh"[All Fields] AND "water"[All Fields]) OR "fresh water"[All Fields] OR "freshwater"[All Fields] OR "freshwaters"[All Fields]

groundwater: "groundwater"[MeSH Terms] OR "groundwater"[All Fields] OR "groundwaters"[All Fields] OR "groundwater's"[All Fields]

marine: "military personnel"[MeSH Terms] OR ("military"[All Fields] AND "personnel"[All Fields]) OR "military personnel"[All Fields] OR "marine"[All Fields] OR "marines"[All Fields]

island: "island's"[All Fields] OR "islands"[MeSH Terms] OR "islands"[All Fields] OR "island"[All Fields]

aquatic: "aquatic"[All Fields] OR "aquatically"[All Fields] OR "aquatics"[All Fields]

Search #2 Exposures: 5,082,359

((((((((((((((((((((((thorium) OR (uranium)) OR (plutonium)) OR (radon)) OR (polonium)) OR (gamma)) OR (alpha)) OR (beta)) OR (radiation)) OR (radionuclide)) OR (radiological)) OR (radioactive)) OR (ionising)) OR (ionizing)) OR (tailings)) OR (NORM)) OR (radioactivity)) OR (U-238)) OR (Th-232)) OR (Ra-226)) OR (Po-210)) OR (Th-228)) OR (Po-208)) OR (dose)) OR (fallout)

Translations

thorium: "thorium"[MeSH Terms] OR "thorium"[All Fields]

uranium: "uranium"[MeSH Terms] OR "uranium"[All Fields] OR "uranium's"[All Fields]

plutonium: "plutonium"[MeSH Terms] OR "plutonium"[All Fields]

radon: "radon"[MeSH Terms] OR "radon"[All Fields] OR "radon's"[All Fields]

polonium: "polonium"[MeSH Terms] OR "polonium"[All Fields]

gamma: "gamma rays"[MeSH Terms] OR ("gamma"[All Fields] AND "rays"[All Fields]) OR "gamma rays"[All Fields] OR "gamma"[All Fields] OR "gamma's"[All Fields] OR "gammae"[All Fields] OR "gammas"[All Fields]

alpha: "alpha"[All Fields] OR "alpha's"[All Fields] OR "alphas"[All Fields]

beta: "BETA"[Journal:__jid9113964] OR "beta"[All Fields]

radiation: "radiate"[All Fields] OR "radiated"[All Fields] OR "radiates"[All Fields] OR "radiating"[All Fields] OR "radiation"[MeSH Terms] OR "radiation"[All Fields] OR "electromagnetic radiation"[MeSH Terms] OR ("electromagnetic"[All Fields] AND "radiation"[All Fields]) OR "electromagnetic radiation"[All Fields] OR "radiations"[All Fields] OR "radiation's"[All Fields] OR "radiator"[All Fields] OR "radiators"[All Fields]

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radiological: "radiological"[All Fields] OR "radiologically"[All Fields] OR "radiology"[MeSH Terms] OR "radiology"[All Fields] OR "radiologic"[All Fields]

radioactive: "radioactively"[All Fields] OR "radioactivity"[MeSH Terms] OR "radioactivity"[All Fields] OR "radioactive"[All Fields] OR "radioactivities"[All Fields]

ionising: "ionising"[All Fields] OR "ionizing"[All Fields]

ionizing: "ionising"[All Fields] OR "ionizing"[All Fields]

tailings: "tailing"[All Fields] OR "tailings"[All Fields]

radioactivity: "radioactively"[All Fields] OR "radioactivity"[MeSH Terms] OR "radioactivity"[All Fields] OR "radioactive"[All Fields] OR "radioactivities"[All Fields]

fallout: "fallout"[All Fields] OR "fallouts"[All Fields]

Search #3: Water Bodies and Exposure found 196,839 articles

((((((((((((((((River) OR (lake)) OR (estuary)) OR (dam)) OR (reservoir)) OR (creek)) OR (waterhole)) OR (stream)) OR (spring)) OR (pond)) OR (surface water)) OR (freshwater)) OR (groundwater)) OR (foreshore)) OR (marine)) OR (island)) OR (aquatic)) AND (((((((((((((((((((((((((thorium) OR (uranium)) OR (plutonium)) OR (radon)) OR (polonium)) OR (gamma)) OR (alpha)) OR (beta)) OR (radiation)) OR (radionuclide)) OR (radiological)) OR (radioactive)) OR (ionising)) OR (ionizing)) OR (tailings)) OR (NORM)) OR (radioactivity)) OR (U-238)) OR (Th-232)) OR (Ra-226)) OR (Po-210)) OR (Th-228)) OR (Po-208)) OR (dose)) OR (fallout))

Repeat search for title and abstract = 48,033

Repeat title and abstract search with additional and for all fields Australia

Boolean search string:

((River[Title/Abstract] OR lake[Title/Abstract] OR estuar*[Title/Abstract] OR dam[Title/Abstract] OR reservoir[Title/Abstract] OR creek[Title/Abstract] OR waterholes[Title/Abstract] OR stream[Title/Abstract] OR spring[Title/Abstract] OR pond[Title/Abstract] OR ‘surface water’[Title/Abstract] OR freshwater[Title/Abstract] OR groundwater[Title/Abstract] OR foreshore[Title/Abstract] OR marine[Title/Abstract] OR island[Title/Abstract] OR aquatic[Title/Abstract]) AND (thorium[Title/Abstract] OR uranium[Title/Abstract] OR plutonium[Title/Abstract] OR radon[Title/Abstract] OR polonium[Title/Abstract] OR gamma[Title/Abstract] OR alpha[Title/Abstract] OR beta[Title/Abstract] OR radiat*[Title/Abstract] OR radionuclide[Title/Abstract] OR radioisotope[Title/Abstract] OR radiological[Title/Abstract] OR ionising[Title/Abstract] OR ionizing[Title/Abstract] OR tailings[Title/Abstract] OR NORM[Title/Abstract] OR radioactiv*[Title/Abstract] OR U-238[Title/Abstract] OR Th-232[Title/Abstract] OR Ra-226[Title/Abstract] OR Po-210[Title/Abstract] OR Th-228[Title/Abstract] OR Po-208[Title/Abstract] OR dose[Title/Abstract] OR fallout[Title/Abstract])) AND (Australia)

Found 1,745 articles

Without Alpha and Beta 1,133 articles found

Without Alpha, Beta and Gamma 994 articles found including all 4 reference articles

Repeat search for title = 1,515 (without the 'AND Australia') Does not find all reference articles

Web of Science Search

Abstract search with additional Australia Search Construct

Boolean search string:
((AB=(River OR lake OR estuar* OR dam OR reservoir OR creek OR waterholes OR stream OR spring OR pond OR 'surface water' OR freshwater OR groundwater OR foreshore OR marine OR island OR aquatic)) AND AB=(thorium OR uranium OR plutonium OR radon OR polonium OR radiat* OR radionuclide OR radioisotope OR radiological OR ionising OR ionizing OR tailings OR NORM OR radioactiv* OR U-238 OR Th-232 OR Ra-226 OR Po-210 OR Th-228 OR Po-208 OR dose OR fallout)) AND AB=(Australia)

Found 1,506 articles and all 4 reference articles.

Including Gamma increases articles to 1,648

Abstract search with additional Australia search construct (topic which includes title, abstract, keywords)

Boolean search string:

((((AB=(River OR lake OR estuar* OR dam OR reservoir OR creek OR waterholes OR stream OR spring OR pond OR 'surface water' OR freshwater OR groundwater OR foreshore OR marine OR island OR aquatic)) AND AB=(thorium OR uranium OR plutonium OR radon OR polonium OR radiat* OR radionuclide OR radioisotope OR radiological OR ionising OR ionizing OR tailings OR NORM OR radioactiv* OR U-238 OR Th-232 OR Ra-226 OR Po-210 OR Th-228 OR Po-208 OR dose OR fallout)))) AND TS=(Australia)

Found 1,812 papers including all 4 reference articles.

Including Gamma increases articles to 2,038

Generic search strings

River OR lake OR estuar* OR dam OR reservoir OR creek OR waterholes OR stream OR spring OR pond OR ‘surface water’ OR freshwater OR groundwater OR foreshore OR marine OR island OR aquatic

thorium OR uranium OR plutonium OR radon OR polonium OR gamma OR alpha OR beta OR radiat* OR radionuclide OR radioisotope OR radiological OR ionising OR ionizing OR tailings OR NORM OR radioactiv* OR U-238 OR Th-232 OR Ra-226 OR Po-210 OR Th-228 OR Po-208 OR dose OR fallout

thorium OR uranium OR plutonium OR radon OR polonium OR gamma OR radiat* OR radionuclide OR radioisotope OR radiological OR ionising OR ionizing OR tailings OR NORM OR radioactiv* OR U-238 OR Th-232 OR Ra-226 OR RN-222 OR Po-210 OR Th-228 OR Po-208 OR dose OR fallout

Final PubMed Search

Remove Alpha and Beta

Keep Gamma

Add AND Australia (All fields)

Final Search string

(((River[Title/Abstract] OR lake[Title/Abstract] OR estuar*[Title/Abstract] OR dam[Title/Abstract] OR reservoir[Title/Abstract] OR creek[Title/Abstract] OR waterholes[Title/Abstract] OR stream[Title/Abstract] OR spring[Title/Abstract] OR pond[Title/Abstract] OR 'surface water'[Title/Abstract] OR freshwater[Title/Abstract] OR groundwater[Title/Abstract] OR foreshore[Title/Abstract] OR marine[Title/Abstract] OR island[Title/Abstract] OR aquatic[Title/Abstract]) OR ('drinking water'[Title/Abstract])) AND ((thorium[Title/Abstract] OR uranium[Title/Abstract] OR plutonium[Title/Abstract] OR radon[Title/Abstract] OR polonium[Title/Abstract] OR gamma[Title/Abstract] OR radiat*[Title/Abstract] OR radionuclide[Title/Abstract] OR radioisotope[Title/Abstract] OR radiological[Title/Abstract] OR ionising[Title/Abstract] OR ionizing[Title/Abstract] OR tailing[Title/Abstract] OR NORM[Title/Abstract] OR radioactiv*[Title/Abstract] OR U-238[Title/Abstract] OR Th-232[Title/Abstract] OR Ra-226[Title/Abstract] OR Po-210[Title/Abstract] OR Th-228[Title/Abstract] OR Po-208[Title/Abstract] OR dose[Title/Abstract] OR fallout[Title/Abstract]) OR (Rn-222[Title/Abstract]))) AND (Australia)

1,250 Articles found

Final Web of Science Search

Remove Alpha and Beta

Keep Gamma

Add AND Australia (Topic)

Final Search String

AB=(River OR lake OR estuar* OR dam OR reservoir OR creek OR waterholes OR 'drinking water' OR stream OR spring OR pond OR ‘surface water’ OR freshwater OR groundwater OR foreshore OR marine OR island OR aquatic) AND AB=(thorium OR uranium OR plutonium OR radon OR polonium OR gamma OR radiat* OR radionuclide OR radioisotope OR radiological OR ionising OR ionizing OR tailings OR NORM OR radioactiv* OR U-238 OR Th-232 OR Ra-226 OR RN-222 OR Po-210 OR Th-228 OR Po-208 OR dose OR fallout) AND TS=(Australia)

2,090 Articles found

213 duplicates found and removed

Searches conducted on 15/9/2019

Appendix 2: Excluded studies following full text screening

1. Dickson, B. L. and A. L. Herczeg (1992). "DEPOSITION OF TRACE-ELEMENTS AND RADIONUCLIDES IN THE SPRING ZONE, LAKE TYRRELL, VICTORIA, AUSTRALIA." Chemical Geology 96(1-2): 151-166.
2. Doering, C. and A. Bollhofer (2016). "A database of radionuclide activity and metal concentrations for the Alligator Rivers Region uranium province." Journal of Environmental Radioactivity 162: 154-159.
3. Edraki, M., T. Baumgartl, D. Mulligan, R. Haymont, M. Australasian Inst and Metallurgy (2006). Post closure management of the Mt Leyshon Gold Mine - Water the integrator. 2nd AusIMM Water in Mining Conference, Brisbane, AUSTRALIA.
4. Fox, D. R. (2006). "Statistical issues in ecological risk assessment." Human and Ecological Risk Assessment 12(1): 120-129.
5. Frostick, A., A. Bollhofer and D. Parry (2011). "A study of radionuclides, metals and stable lead isotope ratios in sediments and soils in the vicinity of natural U-mineralisation areas in the Northern Territory." Journal of Environmental Radioactivity 102(10): 911-918.
6. Gilfillan, N. R. and H. Timmers (2012). Detection and tracing of the medical radioisotope I-131 in the Canberra environment. 1st Heavy Ion Accelerator Symposium on Fundamental and Applied Science (HIAS), Australian Natl Univ, Canberra, AUSTRALIA.
7. Holdway, D. A. (1992). "Uranium mining in relation to toxicological impacts on inland waters." Ecotoxicology 1(2): 75-88.
8. Kleinschmidt, R. (2005). Residual radioactivity from the treatment of water for urban domestic applications. 3rd International Conference on the Impact of Environmental Factors on Health, Bologna, ITALY.
9. Loveless, A. M., C. E. Oldham and G. J. Hancock (2008). "Radium isotopes reveal seasonal groundwater inputs to Cockburn Sound, a marine embayment in Western Australia." Journal of Hydrology 351(1-2): 203-217.
10. Markich, S. J. (2002). "Uranium speciation and bioavailability in aquatic systems: an overview." ScientificWorldJournal 2: 707-729.
11. McMaster, S. A., B. N. Noller, C. L. Humphrey, M. A. Trenfield and A. J. Harford (2021). "Speciation and partitioning of uranium in waterbodies near Ranger Uranium Mine." Environmental Chemistry 18(1): 12-19.
12. Murakami, T. (2005). Mechanisms of long-term U transport under oxidizing conditions. Symposium on Actinides-Basic Science, Applications and Technology held at the 2005 MRS Fall Meeting, Boston, MA.
13. Murphy, M. J., C. H. Stirling, A. Kaltenbach, S. P. Turner and B. F. Schaefer (2014). "Fractionation of U-238/U-235 by reduction during low temperature uranium mineralisation processes." Earth and Planetary Science Letters 388: 306-317.
14. Murray, A. S., A. Johnston, P. Martin, G. Hancock, R. Marten and J. Pfitzner (1993). "TRANSPORT OF NATURALLY-OCCURRING RADIONUCLIDES BY A SEASONAL TROPICAL RIVER, NORTHERN AUSTRALIA." Journal of Hydrology 150(1): 19-39.
15. Noller, B. N. and B. T. Hart (1993). "URANIUM IN SEDIMENTS FROM THE MAGELA CREEK CATCHMENT, NORTHERN-TERRITORY, AUSTRALIA." Environmental Technology 14(7): 649-656.

16. Noller, B. N., R. A. Watters and P. H. Woods (1997). "The role of biogeochemical processes in minimising uranium dispersion from a mine site." Journal of Geochemical Exploration 58(1): 37-50.
17. Payne, T. E. and P. L. Airey (2006). "Radionuclide migration at the Koongarra uranium deposit, Northern Australia - Lessons from the Alligator Rivers analogue project." Physics and Chemistry of the Earth 31(10-14): 572-586.
18. Pirlo, M. C. (2001). Geochemical modeling of wastewater disposal at the Honeymoon in situ leach uranium mine, South Australia. 10th International Symposium on Water-Rock Interaction, Villasimius, Italy.
19. Riethmuller, N., S. J. Markich, R. A. Van Dam and D. Parry (2001). "Effects of water hardness and alkalinity on the toxicity of uranium to a tropical freshwater hydra (Hydra viridissima)." Biomarkers 6(1): 45-51.
20. Ruff, T. A. (2015). "The humanitarian impact and implications of nuclear test explosions in the Pacific region." International Review of the Red Cross 97(899): 775-813.
21. Ryan, B., A. Bollhöfer and P. Martin (2008). "Radionuclides and metals in freshwater mussels of the upper South Alligator River, Australia." J Environ Radioact 99(3): 509-526.
22. Sanders, C. J., I. R. Santos, M. Sadat-Noori, D. T. Maher, C. Holloway, B. Schnetger and H. J. Brumsack (2017). "Uranium export from a sandy beach subterranean estuary in Australia." Estuarine Coastal and Shelf Science 198: 204-212.
23. Santos, I. R., P. L. M. Cook, L. Rogers, J. de Weys and B. D. Eyre (2012). "The "salt wedge pump": Convection-driven pore-water exchange as a source of dissolved organic and inorganic carbon and nitrogen to an estuary." Limnology and Oceanography 57(5): 1415-1426.
24. Sinclair, A., K. Tayler, R. van Dam and A. Hogan (2014). "Site-specific water quality guidelines: 2. Development of a water quality regulation framework for pulse exposures of mine water discharges at a uranium mine in northern Australia." Environ Sci Pollut Res Int 21(1): 131-140.
25. Skirrow, R. G., E. N. Bastrakov, K. Baroncii, G. L. Fraser, R. A. Creaser, C. M. Fanning, O. L. Raymond and G. J. Davidson (2007). "Timing of iron oxide Cu-Au-(U) hydrothermal activity and Nd isotope constraints on metal sources in the Gawler craton, south Australia." Economic Geology 102(8): 1441-1470.
26. Smith, B. S., D. P. Child, D. Fierro, J. J. Harrison, H. Heijnis, M. A. C. Hotchkis, M. P. Johansen, S. Marx, T. E. Payne and A. Zawadzki (2016). "Measurement of fallout radionuclides, Pu-239,Pu-240 and Cs-137, in soil and creek sediment: Sydney Basin, Australia." Journal of Environmental Radioactivity 151: 579-586.
27. Tarhan, L. G., N. J. Planavsky, X. Wang, E. J. Bellefroid, M. L. Droser and J. G. Gehling (2018). "The late-stage "ferruginization" of the Ediacara Member (Rawnsley Quartzite, South Australia): Insights from uranium isotopes." Geobiology 16(1): 35-48.
28. Trenfield, M. A., S. McDonald, K. Kovacs, E. K. Lesher, J. M. Pringle, S. J. Markich, J. C. Ng, B. Noller, P. L. Brown and R. A. van Dam (2011). "Dissolved organic carbon reduces uranium bioavailability and toxicity. 1. Characterization of an aquatic fulvic acid and its complexation with uranium[VI]." Environ Sci Technol 45(7): 3075-3081.
29. Trenfield, M. A., C. J. Pease, S. L. Walker, S. J. Markich, C. L. Humphrey, R. A. van Dam and A. J. Harford (2021). "Assessing the Toxicity of Mine-Water Mixtures and the Effectiveness of Water

Quality Guideline Values in Protecting Local Aquatic Species." Environ Toxicol Chem 40(8): 2334-2346.

30. Veeh, H. H., W. S. Moore and S. V. Smith (1995). "THE BEHAVIOR OF URANIUM AND RADIUM IN AN INVERSE ESTUARY." Continental Shelf Research 15(13): 1569-1583.
31. Wallbrink, P. J. and A. S. Murray (1994). "FALLOUT OF BE-7 IN SOUTH EASTERN AUSTRALIA." Journal of Environmental Radioactivity 25(3): 213-228.
32. Webb, J. A., D. Fabel, B. L. Finlayson, M. Ellaway, S. Li and H. P. Spiertz (1992). "DENUDATION CHRONOLOGY FROM CAVE AND RIVER TERRACE LEVELS - THE CASE OF THE BUCHAN KARST, SOUTHEASTERN AUSTRALIA." Geological Magazine 129(3): 307-317.
33. Wethered, A. S., T. J. Ralph, H. G. Smith, K. A. Fryirs and H. Heijnis (2015). "Quantifying fluvial (dis)connectivity in an agricultural catchment using a geomorphic approach and sediment source tracing." Journal of Soils and Sediments 15(10): 2052-2066

Appendix 3: Risk or bias assessments for included radiological risk studies and reviews

Table 6: Assessment of Abdelouas (2006) review (tool developed by NHMRC for assessment of existing guidance/guidelines/reviews, administrative and technical criteria adapted from AGREE tool).

Criteria have been colour-coded to assess minimum requirements as follows: 'Must have', 'Should have' or 'May have'

	Criteria	Y/N/NA	Notes
Overall guidance/advice development process			
	Are the key stages of the organisation's advice development processes compatible with Australian processes?	N/A	Not an advice/guideline product
	Are the administrative processes documented and publicly available?	N/A	Not an advice/guideline product
	Was the work overseen by an expert advisory committee? Are potential conflicts of interest of committee members declared, managed and/or reported?	N	Not an advice/guideline product so not overseen by expert advisory committee; interests not declared
	Are funding sources declared?	N	Funding sources for the review are not reported
	Was there public consultation on this work? If so, provide details.	N/A	Not an advice/guideline product
	Is the advice peer reviewed? If so, is the peer review outcome documented and/or published?	Y	It is reasonable to assume that this paper underwent peer review before publication in a journal
	Was the guidance/advice developed or updated recently? Provide details.	N/A	Not an advice/guideline product
Evidence review parameters			
	Are decisions about scope, definitions and evidence review parameters documented and publicly available?	N	No details provided
	Is there a preference for data from studies that follow agreed international protocols or meet appropriate industry standards?	Unknown	No details provided
	Does the organisation use or undertake systematic literature review methods to identify and select data underpinning the advice? Are the methods used documented clearly?	N	No details provided
	If proprietary/confidential studies or data are considered by the agency, are these appropriately described/recorded?	N	The review appears to summarise and synthesise published literature only.
	Are inclusion/exclusion criteria used to select or exclude certain studies from the review? If so, is justification provided?	N	No details provided
	Does the organisation use or adopt review findings or risk assessments from other organisations? What process was used to critically assess these external findings?	Unknown	No details provided
	Can grey literature such as government reports and policy documents be included?	Y	There are mention of several international agency/government reports or policy documents reported in the bibliography.
	Is there documentation and justification on the selection of a toxicological endpoint for use as point of departure for health-based guideline derivation?	N/A	
Evidence search			
	Are databases and other sources of evidence specified?	N	No details provided
	Does the literature search cover at least more than one scientific database as well as additional sources (which may include government reports and grey literature)?	N	No details provided
	Is it specified what date range the literature search covers? Is there a justification?	N	No details provided
	Are search terms and/or search strings specified?	N	No details provided
	Are there any other exclusion criteria for literature (e.g. publication language, publication dates)? If so, what are they and are they appropriate?	N	No details provided

	Criteria	Y/N/NA	Notes
Critical appraisal methods and tools			
	Is risk of bias of individual studies taken into consideration to assess internal validity? If so, what tools are used? If not, was any method used to assess study quality?	N	No details appear to be provided on domains/tools that are considered in risk of bias assessments or other study quality assessments.
	Does the organisation use a systematic or some other methodological approach to synthesise the evidence (i.e. to assess and summarise the information provided in the studies)? If so, provide details.	N	No details provided on how the information from the included studies was synthesised – narrative summary was provided.
	Does the organisation assess the overall certainty of the evidence and reach recommendations? If so, provide details.	N	No details provided
Derivation of health-based guideline values			
	Is there justification for the choice of uncertainty and safety factors?	N/A	
	Are the parameter value assumptions documented and explained?	N/A	
	Are the mathematical workings/algorithms clearly documented and explained?	N/A	
	Does the organisation take into consideration non-health related matters to account for feasibility of implementing the guideline values (e.g. measurement attainability)?	N/A	
	Is there documentation directing use of mechanistic, mode of action, or key events in adverse outcome pathways in deriving health-based guideline values?	N/A	
	If expert judgement is required, is the process documented and published?	N/A	
	Is dose response modelling (e.g. BMDL) routinely used?	N/A	
	Has the organisation's policy for dealing with substances for which a non-threshold mode of action may be applicable in humans been articulated and recorded?	N/A	
	If applicable: For carcinogens, what is the level of cancer risk used by the organisation to set the health-based guideline value?	N/A	
	Reviewer's comments		The paper is a general review that looks at worldwide uranium mill tailings and their impact. The paper provides a summary of previous findings without reporting methods that demonstrate a critical analysis of the papers and reports under consideration or explanation of any data analysis that led to the review conclusions. This is a general review, relevant sections of which could potentially provide some general information to support review findings regarding the health risks from exposure to mill tailings.
	Useful for answering primary research question?	Partially	*Include to provide supporting information*
	Useful for answering secondary research questions?	Partially	

Table 7: Risk-of-bias assessment of Brugger et al. (2005) (adapted from OHAT RoB tool, Table 5 in OHAT Handbook (OHAT, 2019)). Questions and domains that are not applicable to cohort, case studies and observational studies are greyed out.

	Study ID: Brugger et al. (2005) – J2 **Study Type:** Site survey, quantitative chemical analysis/testing	**Risk of Bias**	**Notes**	**Risk of bias rating (++/+/-/--)**
Q	**Selection bias**			
1.	**Randomisation**	**N/A**	Randomization: not applicable to cohort, case studies and observational studies	
2.	**Allocation concealment**	**N/A**	Allocation concealment: not applicable to cohort, case studies and observational studies	
3.	Comparison groups appropriate	No	Samples taken at multiple sites including springs and bores in the area and several sites in the hot springs. Samples were collected at 2 different time points (April and July 2001).	+
	Confounding bias			
4.	Confounding (design/analysis)	Yes	Researchers worked to address confounding by comparing results at a number of locations and by conducting testing at 2 different time points. Researchers note that while care was taken to avoid local environmental contamination, there is a risk of environmental contamination affecting results. The paper notes that other water sources may not represent subsurface conditions because the discharge rates of the springs is unknown and the bore and wells could not be purged.	-
	Performance Bias			
5.	**Identical experimental conditions**	**N/A**	Identical experimental conditions: not applicable to cohort, case studies and observational studies	
6.	**Blinding of researchers during study?**	**N/A**	Blinding of researchers during study?: not applicable to cohort, case studies and observational studies	
	Attrition/Exclusion Bias			
7.	Missing outcome data	Yes	Results were reported for each site. Some samples were discarded due to contamination.	-
	Detection Bias			
8.	Exposure characterisation - Characteristics of water, rock and gas sampling: sampling/measurements/ analytical methods	No	Gas, sediment and rock were sampled from the hot springs. Water samples taken were collected using multiple treatment/non treatment options. Containers were consistent across samples and were flushed with sample water before collection. Collection devices were also flushed and samples from the collection devices were collected for field analysis. Temperature, pH, Eh, Electrical conductivity (EC) and dissolved oxygen (DO) where tested onsite close to the time of collection. Gas samples collected on 2 occasions (April and July). Some samples were discarded due to contamination.	+
9.	Outcome assessment	Possible	Instruments to conduct measurements were calibrated before use using prepared standards.	-

	- Causality: conclusions drawn from data analysis		Dissolved oxygen was measured using a test kit. Uncertainties were estimated by measuring standards and 4 replicates of samples. Alkalinity and acidity measured using standard methods. Uncertainty of results was determined based on replicate analyses. Testing using chromatography in testing laboratories utilised reproducibility to estimate testing uncertainty. Conclusions on water sources and characterization of the hydrothermal system drawn from testing results. Given the possibility of environmental contamination, there is possible bias in results obtained.	
	Selective Reporting Bias			
10.	Outcome reporting	Yes	Results from the hot springs was compared with results from other springs, bore and well waters. The paper notes that the other water sources may not represent subsurface conditions because the discharge rates of the springs is unknown and the bore and wells could not be purged.	-
	Other Sources of Bias			
11.	Other threats (e.g. statistical methods appropriate; researchers adhered to the study protocol	No	Uncertainty at some sites was accounted for by high content of organic matter.	+
	Overall risk of bias rating:			-

Risk of bias rating:

Definitely low risk of bias (++)	++	Probably low risk of bias (+)	+	Probably high risk of bias (-)	-	Definitely high risk of bias (--)	--

Table 8: Risk-of-bias assessment of Ferguson et al. (2011) (adapted from OHAT RoB tool, Table 5 in OHAT Handbook (OHAT, 2019)). Questions and domains that are not applicable to cohort, case studies and observational studies greyed out.

	Study ID: Ferguson et al. (2011) – J3 **Study Type:** Observational study	**Risk of Bias**	**Notes**	**Risk of bias rating (++/+/-/--)**
	Selection bias			
1.	**Randomisation**	**N/A**	Randomization: not applicable to cohort, case studies and observational studies	
2.	**Allocation concealment**	**N/A**	Allocation concealment: not applicable to cohort, case studies and observational studies	
3.	Comparison groups appropriate	Yes	Data collected over a long period of time was assessed, but changes have also occurred to practices (e.g. sample collection, analytical techniques) over this time which raises uncertainty about any observed changes over time.	-
	Confounding bias			
4.	Confounding (design/analysis)	Yes	Assesses complex inter-relationship of mine site water management, hydrology, climate, ecotoxicology, monitoring design and implementation and interpretation. Data over time was assessed, but changes have also occurred over time to practices and testing procedures.	-
	Performance Bias			
5.	**Identical experimental conditions**	**N/A**	**Identical experimental conditions: not applicable to Cohort, Case studies and Observational studies**	
6.	**Blinding of researchers during study?**	**N/A**	**Blinding of researchers during study?: not applicable to Cohort, Case studies and Observational studies**	
	Attrition/Exclusion Bias			
7.	Missing outcome data	No	Data has been provided and arranged to make it comparable across the years.	+
	Detection Bias			
8.	Exposure characterisation - Data analysed - Data collection timelines	Yes	Use of historical data sets to inform understanding of hydrological processes affecting water quality and current regulatory regimes. The paper focuses on assessing the underlying scientific basis for the current regime. Flow rates at the creek are episodic, sampling is taken on a regular timeframe meaning that increased values may be missed if sampling does not coincide with period of heavy rainfall.	-
9.	Outcome assessment	Yes	There is insufficient data to accurately analyse the extend of time lag between upstream and downstream monitoring sites and the implication for water quality. Range of outcomes assessed including water quality, chemical concentrations, flow rates. No link between water quality monitoring and hydrologic flow.	-
	Selective Reporting Bias			
10.	Outcome reporting	Yes	Data collected over the years has been adjusted to align with weeks since the beginning of the wet season to make them comparable. Data is affected by changes to sampling processes and work practice changes over time.	-
	Other Sources of Bias			

11.	Other threats (e.g. statistical methods appropriate; researchers adhered to the study protocol	Yes	Changes to guidelines have resulted in changes to the trigger values over time and the allowable levels of chemicals and uranium. High levels of ecological research needed in the area to determine the impact of the mining on the local area.	-
	Overall risk of bias rating:		**Probably high risk of bias**	-

Risk of bias rating:

Definitely low risk of bias (++)	++	Probably low risk of bias (+)	+	Probably high risk of bias (-)	-	Definitely high risk of bias (--)	--

Table 9: Risk-of-bias assessment of Frostick et al. (2008) (adapted from OHAT RoB tool, Table 5 in OHAT Handbook (OHAT, 2019)). Questions and domains that are not applicable to cohort, case studies and observational studies are greyed out.

Study ID: Frostick et al. (2008) – J4 **Study Type:** Quantitative chemical analysis/testing Observational study		**Risk of Bias**	**Notes**	**Risk of bias rating (--/-/+/++)**
	Selection bias			
1.	**Randomization**	**N/A**	Randomization: not applicable to Cohort, Case studies and Observational studies	
2.	**Allocation concealment**	**N/A**	Allocation concealment: not applicable to Cohort, Case studies and Observational studies	
3.	Comparison groups appropriate - Different sites sampled	No	Study describes the presence of stable lead isotopes, radionuclides and trace metals within sediments and soils at four different locations within Cooper Creek catchment, on or adjacent to the decommissioned Nabarlek Uranium mine. Control site selected upstream of the mine lease. Probable low risk of bias as there is indirect evidence that sites were similar across the different exposure types (I.e., location in relation to mine); however, there may be variations in the characteristics of core sample sites	+
	Confounding bias			
4.	Confounding (design/analysis) - background radiation vs. Mining material radiation etc. - Other sources of radiation	Yes	The authors have identified probable confounder in the discussion - erosion of radiogenic material could potentially have influenced the Pb isotope ratios in sediments downstream of Nabarlek before mining started. Indicated by the presence of radiogenic material throughout deeper pre-mining sections of the cores. Tried to adjust for in design or analysis – taking core and surface samples, using upstream and downstream sites. Potential for unintentional contamination of samples Unlikely that other radiation that could skew the results was present during sample collection, transport and analysis.	-
	Performance Bias			
5.	**Identical experimental conditions**	**N/A**	Identical experimental conditions: not applicable to Cohort, Case studies and Observational studies	
6.	**Blinding of researchers during study?**	**N/A**	Blinding of researchers during study?: not applicable to Cohort, Case studies and Observational studies	
	Attrition/Exclusion Bias			
7.	Missing outcome data	No	All samples were analysed and results reported.	+
	Detection Bias			
8.	Sample characterisation - Characterisation of soil samples: sampling/measurements/ analytical methods - Characterisation of isotope distribution	No	Acceptable methods for measuring exposure – core and surface samples collected at each site, consistent amount of amount of sediment recovered at each location, treated using same methods. Combination of stable Pb isotope ratio, trace metal and radionuclide fingerprinting techniques (Gamma Spectrometry and ICPMS) used to determine the sediment deposition history and extent of erosion and pollution. Site selection and sample selection is appropriate	+

9.	Outcome assessment - Causality: conclusions drawn from data analysis	Possible	Objective outcome assessment, consistency in measurement of outcomes - combination of stable Pb isotope ratio, trace metal and radionuclide fingerprinting techniques (Gamma Spectrometry and ICPMS) used to determine the sediment deposition history and extent of erosion and pollution. Large variation of error – question of repeatability Given possible issue of confounders there may be questions about the conclusions that have been drawn	-
	Selective Reporting Bias			
10.	Outcome reporting	No	Expected outcomes have been reported, based on the methods section. Study protocol not available	+
	Other Sources of Bias			
11.	Other threats (e.g. statistical methods appropriate; researchers adhered to the study protocol)	Unknown	The authors have used statistical analysis, increases confidence in the study findings.	+
	Overall risk of bias rating:		**Probable low risk of bias**	+

Risk of bias rating:

Definitely low risk of bias (++)	++	Probably low risk of bias (+)	+	Probably high risk of bias (-)	-	Definitely high risk of bias (--)	--

Table 10: Risk-of-bias assessment of Hancock et al. (2006) (adapted from OHAT RoB tool, Table 5 in OHAT Handbook (OHAT, 2019)). Questions and domains that are not applicable to Cohort, Case studies and Observational studies greyed out.

Study ID: Hancock et al. (2006) – J5 **Study Type:** Modelling of erosional stability and impact on water quality		**Risk of Bias**	**Notes**	**Risk of bias rating (++/+/-/--)**
	Selection bias			
1.	**Randomization**	**N/A**	Randomization: not applicable to Cohort, Case studies and Observational studies	
2.	**Allocation concealment**	**N/A**	Allocation concealment: not applicable to Cohort, Case studies and Observational studies	
3.	Comparison groups appropriate	Yes	Field measurements used to compare modelling findings, long term measurements needed to confirm modelling data.	-
	Confounding bias			
4.	Confounding (design/analysis)	Yes	Leaching of radionuclides from the soil surface by runoff water was not accounted for and was assumed to be negligible. The sediment concentration predictions did not consider the presence of sediment containment ponds which are present in some of the streams and may result in a discharge of sediment if they are breached. The impact of feral animals such as pigs and horses on the site were not taken into consideration.	--
	Performance Bias			
5.	**Identical experimental conditions**	**N/A**	Identical experimental conditions: not applicable to Cohort, Case studies and Observational studies	
6.	**Blinding of researchers during study?**	**N/A**	Blinding of researchers during study?: not applicable to Cohort, Case studies and Observational studies	
	Attrition/Exclusion Bias			
7.	Missing outcome data	Yes	A full assessment of radiological impact on downstream communities cannot be attempted as it requires further information on long-term radionuclide dispersion and deposition in the Cooper Creek system and bioaccumulation into aquatic foods.	-
	Detection Bias			
8.	Exposure characterisation - Modelling of soil erosion - Modelling of radionuclide flux into waterways	Yes	Initial erosion calculations did not take into account site specific field data. The calculations for this paper took site specific soil texture, vegetation etc into consideration for the calculations. Sediment loads to the water systems was estimated using calculations. Testing was performed on soil samples and the values used with the calculations from the erosion modelling to determine estimated radionuclide flux passing into the waterways.	-
9.	Outcome assessment - Modelling results	No	Published methods used for testing of radionuclide specific activities and quality control measures. Erosion – published methods and models used to assess erosion. These methods and models have been previously used in similar environments of tropical Australia.	+
	Selective Reporting Bias			

10.	Outcome reporting	No	Results of analysis and modelling are provided. Water quality trigger values reported for downstream site and compared to estimated sediment rates. Results from modelling were compared with results from other studies.	+
	Other Sources of Bias			
11.	Other threats (e.g. statistical methods appropriate; researchers adhered to the study protocol	Yes	Authors suggest that site specific and long-term monitoring is needed to evaluation the methodology presented in this paper.	-
	Overall risk of bias rating:		**Probably high risk of bias**	-

Risk of bias rating:

Definitely low risk of bias (++)	++	Probably low risk of bias (+)	+	Probably high risk of bias (-)	-	Definitely high risk of bias (--)	--

Table 11: Risk-of-bias assessment of Kleinschmidt et al. (2007) (adapted from OHAT RoB tool, Table 5 in OHAT Handbook (OHAT, 2019)). Questions and domains that are not applicable to Cohort, Case studies and Observational studies are greyed out.

	Study ID: Kleinschmidt et al. (2007) – J6 **Study Type:** Water and waste products testing, exposure computer modelling	**Risk of Bias**	**Notes**	**Risk of bias rating (--/-/+/++)**
	Selection bias			
1.	**Randomization**	**N/A**	Randomization: not applicable to Cohort, Case studies and Observational studies	
2.	**Allocation concealment**	**N/A**	Allocation concealment: not applicable to Cohort, Case studies and Observational studies	
3.	Comparison groups appropriate - Different sites sampled - Controls	Yes	The study conducted testing for naturally occurring radionuclides across a range of sites. The sites represented a range of different treatment plants, utilising a range of treatment methods. For some of the treatment methods, only one site was identified and sampled, increasing the risk of bias. International standard reference solutions used as controls for testing, reducing the introduction of bias in the testing process.	-
	Confounding bias			
4.	Confounding (design/analysis) - Occupational exposure	Yes	The study did not provide sufficient information regarding occupational co-exposures for the modelling conducted in the study.	-
	Performance Bias			
5.	**Identical experimental conditions**	**N/A**	Identical experimental conditions: not applicable to Cohort, Case studies and Observational studies	
6.	**Blinding of researchers during study?**	**N/A**	Blinding of researchers during study?: not applicable to Cohort, Case studies and Observational studies	
	Attrition/Exclusion Bias			
7.	Missing outcome data	No	Test result data and modelling data is presented.	+
	Detection Bias			
8.	Exposure characterisation - Characteristics of soil samples: sampling/measurements/ analytical methods - Computer modelling	Yes	The methods used for testing of the radionuclides are validated methods conducted within a quality system certified laboratory system. Repeat sampling or sampling of similar environments was not conducted. This means that for some treatment methods an individual result is used as the assumed value for that treatment type. The computer modelling software used to calculate dose and health risks is benchmarked and validated software.	-
9.	Outcome assessment	No	The testing conducted by the laboratory was performed objectively and with approved methods. Computer modelling has been conducted using testing results from sludge testing as assumption values, further testing, would make the modelling results more applicable to other sites.	+

	Selective Reporting Bias			
10.	Outcome reporting	No	The expected outcomes have been reported, based on information provided in the methods section. Study protocols are not available.	+
	Other Sources of Bias			
11.	Other threats (e.g. statistical methods appropriate; researchers adhered to the study protocol	Unknown		
	Overall risk of bias rating:			-

Risk of bias rating:

Definitely low risk of bias (++)	++	Probably low risk of bias (+)	+	Probably high risk of bias (-)	-	Definitely high risk of bias (--)	--

Table 12: Risk-of-bias assessment of Lottermoser et al. (2005) (adapted from OHAT RoB tool, Table 5 in OHAT Handbook (OHAT, 2019)). Questions and domains that are not applicable to Cohort, Case studies and Observational studies greyed out.

	Study ID: Lottermoser et al. (2005) – J7 Study Type: Quantitative chemical testing/analysis	Risk of Bias:	Notes	Risk of bias rating (++/+/-/--)
	Selection bias			
1.	Randomization	N/A	Randomization: not applicable to Cohort, Case studies and Observational studies	
2.	Allocation concealment	N/A	Allocation concealment: not applicable to Cohort, Case studies and Observational studies	
3.	Comparison groups appropriate	Yes	Samples taken during dry season only, at two time points (1999, 2003). Surface and groundwaters collected, flowing/stagnant samples taken from different location to evaluate seepage. Samples taken from local dam to represent local background levels for a control. Results of tailings compared to those taken before capping of the tailing.	+
	Confounding bias			
4.	Confounding (design/analysis)	No	Radiometric survey data was collected in a way to ensure results represented large soil/rock units. Samples collected from controls provided background readings for the area.	+
	Performance Bias			
5.	Identical experimental conditions	N/A	Identical experimental conditions: not applicable to Cohort, Case studies and Observational studies	
6.	Blinding of researchers during study?	N/A	Blinding of researchers during study?: not applicable to Cohort, Case studies and Observational studies	
	Attrition/Exclusion Bias			
7.	Missing outcome data	No	All outcome data was presented.	+
	Detection Bias			
8.	Exposure characterisation - Sample collection	No	Testing conducted on seepage samples, standing water from evaporative pools. Samples of ground and surface water , tailings, mineral precipitates, pond and stream sediments were collected. Ground radiometric survey conducted using portable spectrometer onsite.	+
9.	Outcome assessment - Sample testing	No	Testing was conducted by recognised laboratories and research centres. Repeat testing of controls and blanks was performed during Mineralogical and geochemical analysis.	+
	Selective Reporting Bias			
10.	Outcome reporting	Yes	Results presented in full. The limited number of water samples analysed does not allow for an evaluation of long term trends developing in ground and surface waters.	-
	Other Sources of Bias			
11.	Other threats (e.g. statistical methods	N/A		

appropriate; researchers adhered to the study protocol	
Overall risk of bias rating:	+

Risk of bias rating:

Definitely low risk of bias (++)	++	Probably low risk of bias (+)	+	Probably high risk of bias (-)	-	Definitely high risk of bias (--)	--

Table 13: Risk-of-bias assessment of Mudd et al. (2010) (adapted from OHAT RoB tool, Table 5 in OHAT Handbook (OHAT, 2019)). Questions and domains that are not applicable to Cohort, Case studies and Observational studies greyed out.

	Study ID: Mudd et al. (2010) – J8 Study Type: Observational study	Risk of Bias:	Notes	Risk of bias rating (++/+/-/--)
	Selection bias			
1.	Randomization	N/A	Randomization: not applicable to Cohort, Case studies and Observational studies	
2.	Allocation concealment	N/A	Allocation concealment: not applicable to Cohort, Case studies and Observational studies	
3.	Comparison groups appropriate	Y	Comparison of pollution loads from the site pre and post rehabilitation. Samples of upstream sites to compare local levels are rare.	-
	Confounding bias			
4.	Confounding (design/analysis)	Y	Local samples have not been routinely collected to analyse background levels	-
	Performance Bias			
5.	Identical experimental conditions	N/A	Identical experimental conditions: not applicable to Cohort, Case studies and Observational studies	
6.	Blinding of researchers during study?	N/A	Blinding of researchers during study?: not applicable to Cohort, Case studies and Observational studies	
	Attrition/Exclusion Bias			
7.	Missing outcome data	Y	Data available presented. Authors note that collection of some samples (e.g. groundwater) has not been undertaken continuously over the period of the environmental monitoring program so some datasets and parameters are incomplete. Data at regular intervals have not been collected.	-
	Detection Bias			
8.	Exposure characterisation	N	Results from monitoring programs presented. The rehabilitation process has been outlined and collected data presented.	+
9.	Outcome assessment	Y	Historical outcomes presented and compared for a range of sample and testing types. Results provided for water quality (onsite and downstream) at different times and infiltration rates. Results reported as part of the rehabilitation process.	-
	Selective Reporting Bias			
10.	Outcome reporting	Y	Historical data presented and evaluated – noting that there is incomplete data so authors unable to accurately account for all pollutants. Some results represent repeat measurements over time, others represent measurements at a snapshot in time.	-
	Other Sources of Bias			
11.	Other threats (e.g. statistical methods appropriate; researchers adhered to the study protocol	N/A		N/A
	Overall risk of bias rating:			-

Risk of bias rating:

Definitely low risk of bias (++)	++	Probably low risk of bias (+)	+	Probably high risk of bias (-)	-	Definitely high risk of bias (--)	--

Table 14: Risk-of-bias assessment tool of van Dam et al. (2002) (adapted from OHAT RoB tool, Table 5 in OHAT Handbook (OHAT, 2019)). Questions and domains that are not applicable to Cohort, Case studies and Observational studies greyed out.

	Study ID: van Dam et al. (2002) – J9 **Study Type:** System monitoring and exposure modelling for effects on ecosystem and human health from surface water contamination	**Risk of Bias:**	**Notes**	**Risk of bias rating** **(--/-/+/++)**
	Selection bias			
1.	**Randomization**	**N/A**	**Randomization: not applicable to Cohort, Case studies and Observational studies**	
2.	**Allocation concealment**	**N/A**	**Allocation concealment: not applicable to Cohort, Case studies and Observational studies**	
3.	Comparison groups appropriate	No	Testing and monitoring of water quality and effects on selected species is performed at multiple affected sites and at control sites including upstream sites and unaffected streams of Magela Creek.	+
	Confounding bias			
4.	Confounding (design/analysis) - Background radiation vs mining	Yes	The fish studies, control streams have been sought in independent streams so that fish movement along the stream doesn't confound data analysis and interpretation. This paper focuses on radiation levels detected in water, other routes of exposure are mentioned/estimated as part of a human health risk assessment but are not otherwise measured/considered in the paper.	-
	Performance Bias			
5.	**Identical experimental conditions**	**N/A**	**Identical experimental conditions: not applicable to Cohort, Case studies and Observational studies**	
6.	**Blinding of researchers during study?**	**N/A**	**Blinding of researchers during study?: not applicable to Cohort, Case studies and Observational studies**	
	Attrition/Exclusion Bias			
7.	Missing outcome data	Yes	System monitoring data is not presented for all activities, reference is provided to other papers that present this data. Modelling input data is presented.	-
	Detection Bias			
8.	Exposure characterisation - Characteristics of ecological monitoring - Computer modelling	No	Monitoring programs of macroinvertebrate and fish conducted over time to assess the impact of uranium levels, including short term monitoring after water release during periods of heavy rainfall. Controls used in monitoring to assess impact directly from mining. Modelling for human health impacts has the input data presented.	+
9.	Outcome assessment	Yes	Utilises published methods for determining site specific trigger values for uranium. These values are published in other papers. Macroinvertebrate and fish community structure data is not reported in this paper, it is referenced from another paper.	-
	Selective Reporting Bias			

10.	Outcome reporting	Yes	Data is referenced for a range of monitoring activities, but primary data is not provided.	-
	Other Sources of Bias			
11.	Other threats (e.g. statistical methods appropriate; researchers adhered to the study protocol	N/A		
	Overall risk of bias rating:			-

Risk of bias rating:

Definitely low risk of bias (++)	++	Probably low risk of bias (+)	+	Probably high risk of bias (-)	-	Definitely high risk of bias (--)	--

Appendix 4: Confidence ratings for included radiological risk papers

Table 15: Confidence Rating for included environmental testing studies

Study outcome (number of studies, study type)	Environmental testing to characterize the hydrothermal system (1 observational environmental study)	Radioactive and radiogenic isotopes testing of environmental sediment samples (1 observational environmental study)	Radioactivity concentrations testing of water treatment plant samples (1 observational environmental study)	Radiological and mineral testing of tailings and environment samples (1 observational environmental study)	**Comment** [(a)]
Study ID	Brugger 2005	Hancock et al., 2006	Kleinschmidt et al., 2007	Lottermoser et al., 2005	
Initial confidence rating	**LOW**	**LOW**	**LOW**	**LOW**	Based on study design as per OHAT (2019, Table 8).
Risk of Bias	Serious. Downgraded to **VERY LOW**.	Not serious.	Serious. Downgraded to **VERY LOW**.	Not serious.	Confidence downgraded due to consistent potential confounding and inconsistent detection bias across studies.
Unexplained inconsistency	Not serious.	Not serious.	Not serious.	Not serious.	Environmental studies seem to be consistent in terms of their findings Confidence not downgraded.
Indirectness	Not serious.	Not serious.	Not serious.	Not serious.	The studies are relevant to the research questions. Confidence not downgraded.
Imprecision	Serious. Cannot downgrade further.	Serious. Downgraded to **VERY LOW**.	Serious. Cannot downgrade further.	Serious. Downgraded to **VERY LOW**.	Small sample sizes render the results imprecise. Confidence remains very low.
Publication bias	Undetected.	Undetected.	Undetected.	Undetected.	No downgrade.
Magnitude	Not large.	Not large.	Not large.	Not large.	Environmental studies with small sample sizes do not fit the classic consideration for magnitude of response. Confidence not upgraded.
Dose response	No.	No.	No.	No.	Environmental studies with small sample sizes do not lend themselves to a dose response. Confidence not upgraded.
Residual confounding	No.	No.	No.	No.	Confidence not upgraded.
Consistency across species/population/study design	No.	Yes Upgraded to **LOW**.	No.	Yes Upgraded to **LOW**.	Consistency observed for some results across two study designs for considered reasonable for upgrading. Confidence upgraded.
Final confidence rating	**VERY LOW**	**LOW**	**VERY LOW**	**LOW**	

a. Table adapted from guidance provided in OHAT (2019, Table 7)

Table 16: Confidence Rating for included monitoring studies

Study outcome (number of studies, study type)	Water quality data review 1 observational study	Environmental monitoring and rehabilitation 1 observational study	System monitoring and exposure modelling 1 observational study	**Comment** [(a)]
Study ID	Ferguson et al., 2011	Mudd,et al., 2010	Van Dam et al, 2002	
Initial confidence rating	**LOW**	**LOW**	**LOW**	Based on study design as per OHAT (2019, Table 8).
Risk of Bias	Serious. Downgraded to **VERY LOW**.	Serious. Downgraded to **VERY LOW**.	Serious. Downgraded to **VERY LOW**.	Confidence downgraded due to consistent potential confounding and inconsistent detection bias across studies.
Unexplained inconsistency	Not serious.	Not serious.	Not serious.	Studies appear to be consistent in terms of their findings.
Indirectness	Not serious.	Not serious.	Not serious.	The studies are relevant to the research questions. Confidence not downgraded.
Imprecision	Not serious.	Serious. Cannot be downgraded further.	Serious. Cannot be downgraded further.	Small sample sizes render the results imprecise. Confidence remains very low.
Publication bias	Undetected.	Undetected.	Undetected.	No downgrade.
Magnitude	Not large.	Not large.	Not large.	Monitoring studies do not fit the classic consideration for magnitude of response. Confidence not upgraded.
Dose response	No.	No.	No.	Monitoring studies do not lend themselves to a dose response. Confidence not upgraded.
Residual confounding	No.	No.	No.	Confidence not upgraded.
Consistency across species/population/study design	No.	No.	No.	Some consistency of outcomes across study designs but not considered enough to warrant upgrading. Confidence not upgraded.
Final confidence rating	**VERY LOW**	**VERY LOW**	**VERY LOW**	

a. Table adapted from guidance provided in OHAT (2019, Table 7)

Table 17: Confidence Rating for included modelling studies

Study outcome (number of studies, study type)	Modelling of erosional stability and impact on water quality (1 observational environmental study)	**Comment** [(a)]
Study ID	Frostick et al., 2006	
Initial confidence rating	**LOW**	Based on study design as per OHAT (2019, Table 8).
Risk of Bias	Serious. Downgraded to **VERY LOW**.	Confidence downgraded due to consistent potential confounding and missing outcome data in the study.
Unexplained inconsistency	Not serious.	Confidence not downgraded.
Indirectness	Not serious.	The study is relevant to the research questions. Confidence not downgraded.
Imprecision	N/A	Single study, unable to assess
Publication bias	Undetected.	No downgrade.
Magnitude	Not large.	Modelling studies do not fit the classic consideration for magnitude of response. Confidence not upgraded.
Dose response	No.	Modelling studies do not lend themselves to a dose response. Confidence not upgraded.
Residual confounding	No.	Confidence not upgraded.
Consistency across species/population/study design	N/A	Not applicable to single study/outcome, unable to assess
Final confidence rating	**VERY LOW**	

a. Table adapted from guidance provided in OHAT (2019, Table 7)