

Australian Government

Department of Agriculture, Water and the Environment Supervising Scientist

Magnesium in Surface Water — Rehabilitation Standard for the Ranger uranium mine

Water and sediment theme

Preface

The Supervising Scientist developed this Rehabilitation Standard to describe the requirements to protect aquatic ecosystems outside of the Ranger Project Area in the Alligator Rivers Region of the Northern Territory from the effects of magnesium in surface water.

This document is part of a series of Rehabilitation Standards for the Ranger uranium mine. It may be updated as additional relevant knowledge becomes available.

This Standard should be cited as follows:

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1. General elements

Scope

1.1 The Rehabilitation Standards for the Ranger uranium mine have been developed in accordance with section 5c of the *Environment Protection (Alligator Rivers Region) Act 1978* and are advisory only.

1.2 The Environmental requirements of the Commonwealth of Australia for the operation of the Ranger uranium mine (Environmental Requirements) (Australian Government 1999) specify the environmental objectives for the rehabilitation of the Ranger uranium mine.

1.3 The Supervising Scientist's Rehabilitation Standards quantify the rehabilitation objectives and recommend specific values based on the best available science that will ensure a high level of environmental protection. These values can be used to

assess the achievement of, or progress towards, the rehabilitation objectives, some of which may not be reached for a significant period of time.

1.4 Until it can be determined that the rehabilitation objectives have or will be reached, there will be an ongoing need to ensure environmental protection during and after rehabilitation, through continued water quality monitoring, including the comparison of water quality data with relevant water quality limits.

Objective

1.5 There is currently no agreed acceptable level of effect to the environment surrounding the Ranger Project Area. In the absence of agreement, the Rehabilitation Standard for magnesium in surface water aims to protect the biodiversity and health of aquatic ecosystems outside of the Ranger Project Area. This includes ecosystems upstream of the mine given that poor water quality within the Ranger Project Area could form a barrier to the movement of aquatic organisms. If an acceptable level of effect is agreed, this standard will be updated accordingly.

Application

1.6 This Rehabilitation Standard should be applied in Magela and Gulungul creeks at the boundary of the Ranger Project Area, downstream from the Ranger uranium mine.

1.7 Given the potentially long time frame between the completion of rehabilitation and the peak delivery of contaminants to surface water, this Rehabilitation Standard will most likely be used to assess predicted magnesium concentrations from modelled scenarios. Ongoing surface water and groundwater monitoring will be required after rehabilitation to continue to ensure the environment is being protected, and to validate and assess confidence in the models.

2. Relevant requirements

Environmental Requirements

2.1 The primary environmental objectives in the Environmental Requirements require that surface waters or groundwater arising from the Ranger uranium mine do not result in any detrimental change to biodiversity or impairment of ecosystem health outside of the Ranger Project Area, including during or following rehabilitation. This Rehabilitation Standard is relevant to the Environmental Requirements listed in Box 1.

Aspirations of Traditional Owners

2.2 The Mirarr Traditional Owners desire that operations at the Ranger uranium mine should not result in any change to the natural water quality of surface waters outside of the Ranger Project Area (Iles 2004). Specifically, as stated in Garde (2013):

...the waters contained within all riparian corridors, (i.e. rivers and billabongs), must be of a quality that is commensurate with non-affected riverine systems and health standards. The principle of 'as low as reasonably achievable' should

not apply to these areas. Instead, the standard of rehabilitation must be as high as is technically possible and level of contamination must be as low as technically possible.

Box 1: Ranger Environmental Requirements relevant to the							
Magnesium Rehabilitation Standard							
1 Environmental protection							
1.1 The company must ensure that operations at Ranger are undertaken in such a way as to							
be consistent with the following primary environmental objectives:							
(a) maintain the attributes for which Kakadu National Park was inscribed on the World							
Heritage list							
(b) maintain the ecosystem health of the wetlands listed under the Ramsar Convention on							
Wetlands (i.e. the wetlands within Stages I and II of Kakadu National Park)							
(d) maintain the natural biological diversity of aquatic and terrestrial ecosystems of the							
Alligator Rivers Region, including ecological processes.							
1.2 In particular, the company must ensure that operations at Ranger do not result in:							
(a) damage to the attributes for which Kakadu National Park was inscribed on the World							
Heritage list							
(b) damage to the ecosystem health of the wetlands listed under the Ramsar Convention							
on Wetlands (i.e. the wetlands within Stages I and II of Kakadu National Park)							
(d) change to biodiversity, or impairment of ecosystem health, outside of the Ranger							
Project Area. Such change is to be different and detrimental from that expected from							
natural biophysical or biological processes operating in the Alligator Rivers Region.							
3 water quality							
3.1 The company must not allow either surface or ground waters arising or discharged from							
the Ranger Project Area during its operation, or during of following rehabilitation, to							
compromise the achievement of the primary environmental objectives.							

3. Recommended values for magnesium

3.1 To protect aquatic ecosystems outside the Ranger Project Area in accordance with the rehabilitation objectives, predicted water quality at the boundary of the Ranger Project Area, reported as 72-hour moving averages, should not exceed the recommended values for the parameters shown in Table 1.

Table 1	Rehabilitation	Standard for	magnesium i	in surface	water, inc	luding t	he
magnes	sium-to-calcium	n mass ratio					

Parameter	Location	Rehabilitation Standard
Dissolved magnesium	In Magela and Gulungul creeks at the boundary of the Ranger Project Area, downstream of the Ranger uranium mine	2.9 mg/L
Dissolved magnesium to calcium (Mg:Ca) mass ratio	In Magela and Gulungul creeks at the boundary of the Ranger Project Area, downstream of the Ranger uranium mine	No greater than 9:1

4. Scientific basis

Guidelines and standards used to develop the recommended values

4.1 Key national (ANZG 2018) and international (USEPA 2016) regulatory authorities acknowledge that the most useful approach for deriving environmental protection guideline values is one that combines multiple lines of evidence, including laboratory-and field-effects data.

4.2 The US Environmental Protection Agency (USEPA) offers an advanced weight-ofevidence framework that enables a quantitative approach for integrating multiple lines of evidence to support decision-making (Cormier et al. 2008, USEPA 2016). The framework recommends a number of analytical approaches that may be compiled and compared to ensure that appropriate guideline values are selected. Recently, ANZG (2018) published complementary guidance on weight-of-evidence approaches to deriving guidelines values from multiple lines of evidence. The weight-of-evidence approach from both jurisdictions was applied in the derivation of the magnesium rehabilitation standard, taking into consideration all relevant laboratory- and fieldeffects data that have been collected by the Supervising Scientist over the past 40 years.

4.3 Derivation of the candidate site-specific guideline value using laboratory-based effects data followed the recommendations in *The Australian and New Zealand Government's Guidelines for Fresh and Marine Water Quality* (ANZECC & ARMCANZ 2000, ANZG 2018).

4.4 Various methods, including those described by the USEPA (Cormier & Suter 2012; USEPA 2016), ANZG (2018) and other independently developed analytical methods, were used to derive field-effects and mesocosm-effects candidate guideline values for magnesium.

4.5 Given the ecological importance of the region surrounding the Ranger uranium mine the magnesium rehabilitation standard has been derived to provide the highest level of protection; at least 99% of species according to the national water quality guidelines (ANZECC & ARMCANZ 2000, ANZG 2018).

Scientific evidence summary

4.6 Ranger mine waste rock is rich in minerals containing magnesium, which are leached and mobilised, and can be easily transported in groundwater and surface waters. Due to its availability and high solubility, magnesium presents a significant risk to the aquatic environment surrounding the Ranger uranium mine, both during operations and after rehabilitation.

4.7 Magnesium has a higher toxicity in the soft receiving waters surrounding the Ranger Project Area than it does in most freshwaters, which is most likely due to the

naturally low concentrations of calcium and other major cations in these waters compared with the test waters used for other studies. The mechanisms of magnesium toxicity are unknown (van Dam et al. 2010).

4.8 The Supervising Scientist has used multiple lines of evidence to assess the effects of magnesium on aquatic biota, ranging from short-term laboratory exposures of single-test species to long-term field exposures of natural biological communities. These laboratory and field studies (summarised in 4.9 to 4.26) have generated significant site-specific information on the biological effects of magnesium, giving us a high level of confidence in the derived magnesium rehabilitation standard.

Laboratory toxicity testing

4.9 The Supervising Scientist has studied the effects of magnesium on local aquatic species in the laboratory for the past 20 years. In this period, more than 250 laboratory experiments have been conducted to investigate magnesium toxicity under different exposure scenarios and in response to factors that are known to modify magnesium toxicity. The results of these studies, summarised here, are described in van Dam et al. (2010), Hogan et al. (2013), Prouse et al. (2015) and Kleinhenz et al. (2019). The potential for increased toxicity due to local water quality conditions in Magela Creek water was accounted for through the use of Magela Creek water as a diluent during laboratory toxicity tests (median pH ~6.0, n = 76,432; temperature range 27–31°C; and low concentrations of dissolved ions).

4.10 The Supervising Scientist's research found that calcium could significantly reduce, and even eliminate, magnesium toxicity to some of the species tested (van Dam et al. 2010). This is important because calcium is present in Ranger mine waters at varying concentrations, and its concentration relative to magnesium may alter the toxicity of magnesium. Additional testing showed that, for some species, magnesium toxicity increased significantly once the magnesium-to-calcium (Mg:Ca) mass ratio exceeded 9:1 (more than nine parts magnesium to one part calcium). Subsequent magnesium toxicity tests were standardised to a Mg:Ca ratio of 9:1.

4.11 The results of these studies were used to derive a site-specific guideline value for magnesium. The nationally accepted species sensitivity distribution approach for deriving water quality guideline values (ANZECC & ARMCANZ 2000) was used to calculate the site-specific guideline value of 2.5 mg/L magnesium, which aims to protect 99% of species in the environment (van Dam et al. 2010).

4.12 The site-specific guideline value of 2.5 mg/L was used to determine the current operational limit of 3.0 mg/L magnesium, which has been implemented in Magela Creek since 2013 and in Gulungul Creek since 2016 (Sinclair et al. 2014, Turner et al. 2016). The operational limit also requires that the corresponding Mg:Ca ratio does not exceed 9:1 (Mg concentration is at or less than nine times the calcium concentration).

Field studies

4.13 Since 1979, the Supervising Scientist has undertaken various field studies to investigate the potential impacts of uranium mining on the aquatic ecosystems, including local biological communities in surface waters surrounding the Ranger Project Area. Much of this work has been used to determine concentrations of magnesium that are considered to be protective of the aquatic environment.

Magela Creek mesocosms

4.14 Field mesocosms, comprising large tubs filled with early dry season creek water, were deployed in the Magela Creek channel in the 2002 dry season. The mesocosms were allowed to colonise naturally with macroinvertebrate, zooplankton, phytoplankton and attached diatom communities, and were then dosed with four concentrations of magnesium sulfate between 2.5 and 68.0 mg/L magnesium. After 4 and 8 weeks of exposure, the mesocosms were sampled and assessed for changes in the biological communities (McCullough 2006, Mooney et al. 2020).

4.15 Results of this work, including reanalyses of the data during 2016–17, demonstrated that phytoplankton (cell counts of key phylogenetic groups such as green algae, as well as algal biomass in the form of chlorophyll *a*) and zooplankton exhibited sensitivity after 4 weeks of exposure. The concentrations that caused a 1% effect on overall algal biomass and zooplankton community structure were 1.5 and 2.6 mg/L magnesium, respectively (Mooney et al. 2020).

Macroinvertebrate communities in lentic water bodies

4.16 Using biological monitoring data from the sampling of up to 14 shallow billabongs or waterbodies over seven annual sampling occasions between 1979 and 2013, the responses of macroinvertebrate communities were assessed across a spatial and temporal gradient of exposure to Ranger mine wastewaters dominated by magnesium sulfate (Humphrey & Chandler 2018). From this 7-year record across 34 years, the 1% effect concentrations for community structure and taxa number were 5.6 and 3.9 mg/L magnesium, respectively.

4.17 Biological effects to assemblages in the mesocosm and billabong studies occurred at low Mg:Ca ratios (between 3.5:1 and 6:1). However, other mechanisms, including ecological interactions, were identified as potential causes of the responses observed at these low Mg:Ca ratios. Because the effect of different Mg:Ca ratios was not specifically studied in both field studies, the relevant Mg:Ca ratio providing protection to aquatic ecosystems was derived from laboratory studies where the relationship between Mg:Ca ratios and effects had been experimentally established (from 4.10 above).

Supporting Lines of Evidence

4.18 A number of studies pertaining to Mg have been completed since the Mg Rehabilitation Standard was first published (2018). The inclusion of new and additional biological effects information arising from these studies did not warrant a re-derivation of the Rehabilitation Standard as the re-calculated number was shown to not

significantly change the Mg value (see Section 4.19/4 below), especially within the context of the accuracy of contaminant egress modelling, which will be used to assess the risk of Mg to receiving waters. Hence, new effects information has only been used as evidence to support the Mg Rehabilitation Standard.

4.19 Recently (2018 to 2019), revisions have been made to two of the toxicity tests used in van Dam et al. (2010) to bring these in line with new guideline derivation guidance (ANZG 2018, Warne et al. 2018), while additional toxicity data have become available for other species, as follows:

- 1. The toxicity estimates arising from the fish species (*Mogurnda mogurnda*) acute 4-day toxicity test in van Dam et al. (2010), were updated using those from a chronic, sub-lethal 7-day toxicity test exposure (Pease et al. *in press*).
- 2. The 4-day toxicity test for the snail species described in van Dam et al. (2010), which is considered an acute exposure (Warne et al. 2018), was extended to longer, chronic exposure periods (9-day and 14-day). However, the sensitivity of the snail remained greatest at the 4-day exposure and so these new 4-day data, together with the original data from van Dam et al (2010) and the 4-day exposure data from Hogan et al (2013), were used in guideline (re-)derivation.
- 3. Toxicity data for two local freshwater mussel species have also been generated since van Dam et al (2010) and reported in (Kleinhenz et al. 2019).
- 4. Including the toxicity estimates from these additional laboratory studies to derive a new site-specific guideline value for magnesium did not significantly change the candidate guideline value. Thus, applying the nationally accepted species sensitivity distribution approach for deriving water quality guideline values (ANZG 2018) to the new dataset gave rise to a site-specific candidate guideline value of 2.4 mg/L. This value is comparable to the van Dam et al (2010) guideline value of 2.5 mg/L and supports the current magnesium Rehabilitation Standard of 2.9 mg/L. Importantly the current Standard is protective of the three species for which the new toxicity data were considered.

4.20 A number of studies were conducted over the period 2018-2020 to address Key Knowledge Needs. The focus of these studies was on key groups of aquatic organisms that have not been represented in laboratory and field toxicity assessments and included flow-dependent invertebrates and aquatic macrophytes.

4.21 Some flow-dependent organisms were relatively sensitive to acute Mg exposures in the laboratory. The acute data (i.e. short-term mortality endpoints) were converted to equivalent-chronic toxicity estimates, with a species sensitivity distribution approach then used to predict the concentration protecting 99% of the population; this proxy protection value for chronic exposure was 3.3 mg/L. This value is comparable to the current Magnesium Rehabilitation Standard, indicating that the Standard will offer protection to this group of organisms from chronic Mg exposure.

4.22 Analysis of the macrophyte communities in mine-water exposed and reference billabongs showed that they were not sensitive to Mg at concentrations less than 100 mg/L.

Direct toxicity assessments

4.23 The Supervising Scientist has undertaken biological toxicity testing of whole mine waters on at least 13 occasions since 1987.

4.24 An analysis of a subset of the data from these Direct Toxicity Assessments (DTAs) was undertaken to identify contaminants in the mine waters that were most likely to be causing toxicity (Trenfield et al. 2017). The analysis indicated that the toxicity of the mine Pond waters tested was primarily caused by uranium. Typically, concentrations of magnesium in the mine Pond waters tested did not approach those reported to be toxic to the test species. Consequently, the results could not be used to inform the magnesium rehabilitation standard.

4.25 The toxicity of seepage water expressing in a tributary of Gulungul Creek, to the west of the Ranger Tailings Storage Facility, was assessed in 2015 using three local species (Trenfield et al. 2017). The sampled seepage water was high in magnesium (350 mg/L) and had a Mg:Ca ratio of 5:1. For two species (snail and duckweed), the toxicity of the seepage water was consistent with the previous findings of van Dam et al. (2010) relating to the ameliorative effect of calcium on magnesium toxicity. For the third species (hydra), the toxicity of the seepage water was greater than expected. This may have been due to a potential contribution to toxicity from other metals in the water. Overall, the results were broadly supportive of the findings of the laboratory and field magnesium studies.

4.26 DTAs of key Ranger mine-water types were conducted to determine if cumulative effects should be expected from Mg-rich mine-waters that contained various contaminant mixtures. This showed that Mg was the primary toxicant in contaminated shallow groundwaters, and Mn was the primary contaminant in process waters. Antagonistic effects (i.e. lower than expected toxicity) were most common and cumulative effects (i.e. greater than expected toxicity) were rarely observed in the DTAs. Hence, the study concluded that it would be appropriate to use the single contaminant COPC guideline values to assess modelled outputs of the future surface water contaminant concentrations.

Recommendations for magnesium

4.27 The integration and evaluation of different lines of evidence through a weight-ofevidence assessment strengthens certainty about conclusions.

4.28 In the case of Ranger rehabilitation, certainty is required around the rehabilitation standard in terms of both consistency amongst the candidate guideline values arising from different lines of evidences (laboratory and field) and confidence that the final guideline value is sufficiently protective of receiving water ecosystems.

4.29 Laboratory, field experimental (mesocosm) and observational (macroinvertebrate community) studies gave rise to similar magnesium candidate guideline values of 2.5-3.1, 1.5–3.1 and 3.9–5.6 mg/L magnesium, respectively, depending on the measured response.

4.30 The laboratory studies showed that the Mg:Ca ratio of 9:1 was sufficiently protective of magnesium toxicity. However, special consideration would be needed if there were scenarios where the Mg concentration was <2.9 mg/L and Mg:Ca ratio was >9:1.

4.31 A conservative rehabilitation standard is recommended to ensure the protection of the biodiversity and health of aquatic ecosystems outside of the Ranger Project Area, noting:

- the wishes of traditional owners (refer to 2.2) and the high conservation value, World Heritage and Ramsar-listed ecosystems surrounding the mine,
- ii) that calcium is not protective of magnesium toxicity for all species, locally (Humphrey & Chandler 2018; Trenfield et al. 2017), elsewhere in Australia's wet–dry tropics (van Dam et al. 2014) and internationally (Pond 2010),
- that toxicity may be greater in receiving waters that receive pulses of saline waters, compared with a slow build up to higher and sustained concentrations (Marshall & Bailey 2004; Prasad et al. 2014; Humphrey & Chandler 2018),
- following from iii), that after mine site closure, opportunities for acclimation to develop in Magela Creek receiving waters may not be available because of normal wet season flushing events and replenishment of (nonacclimated) biota during the wet season from external recruitment sources.

4.32 Taking these factors into account, the magnesium rehabilitation standard was determined as the mean of the lowest available candidate guideline values, for which there was deemed to be sufficient confidence, for each of the laboratory (2.5 mg/L), mesocosm (2.6 mg/L) and field (3.9 mg/L) studies. This value is 2.9 mg/L. This approach to deriving the magnesium rehabilitation standard is consistent with the best available international guidance.

4.33 In addition, and to prevent the likelihood of higher magnesium toxicity as a result of increasing the Mg:Ca ratio (e.g. if significant seepage from tailings enters Magela Creek), the magnesium rehabilitation standard includes the recommendation for the Mg:Ca ratio in surface waters to be less than 9:1.

4.34 The recommended values for magnesium and the Mg:Ca ratio should be compared with 72-hour moving average values based on appropriately modelled water quality scenarios. A 72-hour duration has been chosen because it represents the shortest exposure duration of the chronic toxicity tests for the various species used in the laboratory studies, and is broadly representative of the short life cycles of many algal and invertebrate species. These short life cycles increase the potential for

exposure of sensitive early life stages to contaminants during the wet season, and also reduce the opportunity for acclimation or development of tolerance. Thus, until further evidence suggests otherwise, the conservative 72-hour duration is required to ensure protection of aquatic species.

5. Future knowledge needs

5.1 Rehabilitation planning can only be based on the best available information at a given time, but this should not preclude the continual improvement of the knowledge base and its subsequent application where directly relevant and possible.

5.2 The Supervising Scientist, through its Key Knowledge Needs, has identified the knowledge required to ensure appropriate management of the key risks to the environment from the rehabilitation of the Ranger uranium mine. For magnesium, these knowledge needs are shown in Table 2.

5.3 The value(s) based on laboratory toxicity testing in this Standard were derived using the methodology prescribed in The Australian and New Zealand guidelines for fresh and marine water quality (ANZECC & ARMCANZ 2000). These Guidelines have recently been revised (ANZG 2018) and in keeping with best practice, the current Standard will be reviewed in due course in line with updated guidance.

ER Link	Key Knowledge Need	Questions
Biodiversity and human health	WS7. Determining the impact of chemical contaminants on aquatic biodiversity and ecosystem health	WS7D. How do acidification events impact upon, or influence the toxicity of contaminants to, aquatic biota?WS7F. Can a contaminant plume in creek channels form a barrier that inhibits organism migration and connectivity (e.g. fish migration, invertebrate drift, gene flow)?

Table 2 Key Knowledge Needs for Magnesium in Surface Water

6. References

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