Australian Government
Department of Agriculture, Water and the Environment
Supervising Scientist

Copper and Zinc 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 copper and zinc in surface water. Standards for other metals including magnesium, manganese and uranium, are published separately.

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:

Supervising Scientist 2021. Copper and zinc in surface water — Rehabilitation Standard for the Ranger uranium mine (version 1). Supervising Scientist Branch, Darwin, NT. http://www.environment.gov.au/science/supervising-scientist/publications/ss-rehabilitation-standards. Cited [Date].

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 time period.

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 Standards for copper and zinc in surface water aim 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 before the peak delivery of contaminants to surface water, this Rehabilitation Standard will most likely be used to assess predicted copper and zinc 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 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 Other Metals 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 or following rehabilitation, to compromise the achievement of the primary environmental objectives.

3. Recommended values for metals in tailings and brine

3.1 A tiered risk assessment of all metals in tailings and brine identified copper and zinc as the two key Contaminants of Potential Concern (COPCs, see section 4). Other key COPCs in the tailings and brine, uranium, manganese and ammonia, had existing site-specific guideline values.

3.2 The guideline values reported in this Standard are site-specific (copper) and site-adapted (zinc), hence they were derived based on local conditions. A site-specific guideline value refers to a guideline value that has been specifically developed using local species and accounts for relevant chemical, physical and/or ecological conditions that occur at a site of interest. A site-adapted guideline value refers to a guideline value that has been adapted, based on existing knowledge, to make it more relevant to the chemical and physical conditions at a site of interest. To protect the 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 copper and zinc in surface water

Parameter	Location	Rehabilitation standard
Dissolved [a] copper	In Magela and Gulungul creeks at the boundary of the Ranger Project Area, downstream of the Ranger uranium mine	0.5 µg/L (72-h moving average)
Dissolved zinc	In Magela and Gulungul creeks at the boundary of the Ranger Project Area, downstream of the Ranger uranium mine	1.5 µg/L (72-h moving average)

[a] Dissolved = <0.45 µm filtered

4. Scientific basis

Guidelines and standards used to develop the recommended values

4.1 This Rehabilitation Standard is based on site-specific and site-adapted guideline values which have been derived for local conditions, as recommended in the *Australian and New Zealand guidelines for fresh and marine water quality* (ANZG 2018). Additional details for the two contaminants are provided in the Appendix.

4.2 Given the ecological importance of the region surrounding the Ranger uranium mine, the rehabilitation standards for copper and zinc are based on guideline values that provide the highest level of protection, i.e. at least 99% of species, as recommended in the national water quality guidelines (ANZG 2018).

Scientific evidence summary

4.3 A mixture of contaminants will be present at high concentrations in the Ranger uranium mine tailings and the concentrated brine that will be disposed of into the Pit 3 void. These contaminants could potentially enter creeks through groundwater egress after rehabilitation. Uranium, manganese and ammonia were elevated in operational discharge waters and so site-specific guideline values had previously been derived for these COPCs. However, other tailings- and brine-related contaminants were at relatively low concentrations in actively discharged release waters during the operational phase of mining and, therefore, they were previously assessed as low-risk (Turner & Jones 2010). Hence, limited site-specific toxicity data had been collected.

4.4 Given the potential for tailings- and brine-related metals to enter creeks during the post-decommissioning phase, a hazard assessment was undertaken to identify which contaminants might pose the greatest risk after rehabilitation (Iles & Humphrey 2014). Eight metals were identified, and Rehabilitation Standards were derived for each of these using national Default Guideline Values (ANZG 2018) or background concentrations present in the creeks during mine operations. These Standards were published in the Metals in Surface Water Rehabilitation Standard (version 1), now superseded following further tiers of assessment, described below.

4.5 Further assessment of the eight trace metals indicated that six were unlikely to be a risk if other site-specific guideline values were met. In particular, the assessment indicated that copper (Cu) and zinc (Zn) may still present a risk even if the guideline value for magnesium, the key limiting COPC, was achieved. Copper was also identified as a key contaminant in process water during the toxicity assessments of whole waters from the mine-site, thereby warranting a greater level of consideration (Trenfield et al. submitted). Consequently, a site-specific and site-adapted guideline value were derived for Cu and Zn respectively.

Copper (Cu)

4.6 A national default guideline value has been published for Cu, i.e. 1.0 µg/L (ANZG 2018). However, this value was derived for fresh waters of moderate hardness and is not recommended for application to the soft surface waters surrounding the Ranger mine. Initially, in the absence of site-specific toxicity data, a reference condition approach was used to generate the previous rehabilitation standard of 0.2 µg/L (median of combined upstream and downstream Magela Creek data for the 2002–2018 period, n = 714). Subsequently, SSB has completed site-specific toxicity testing and generated a site-specific guideline values for Cu in Magela Creek water using toxicity estimates for seven local species (Table A1). The site-specific guideline value of 0.5 µg/L is considered 'moderate reliability' under the criteria recommended by Warne et al. (2018).

Zinc (Zn)

4.7 A national default guideline value has been published for Zn, i.e. 2.4 µg/L (ANZG 2018). However, given the preference for guideline values derived for local conditions (section 4.1), site-specific and site-adapted toxicity data were generated for Zn. Site-specific toxicity estimates were acquired from testing of seven local species in Magela Creek water (Table A2). These estimates were combined with 22 published toxicity estimates that were adjusted to the local water quality conditions using a published model (CCME 2018, Table A2). This approach used a "preferred" dataset size (≥15 species) and resulted in a significantly improved fit and reliability of the Species Sensitivity Distribution over that relying only on site-specific toxicity estimates. It was deemed appropriate because Zn research has been conducted internationally to determine the relationships between biological effects and key toxicity modifying factors (i.e. pH, hardness and DOC). This collective site-adapted dataset was used to derive a guideline value of 1.5 µg/L, considered to be of 'moderate-reliability". The use of the CCME algorithm, which has not been validated in low-hardness waters, reduces the reliability of the guideline value. Once a model becomes available that has been validated in low hardness waters, it should be used to revise the guideline value and improve its reliability. The guideline value is classified as 'site-adapted' rather than 'site-specific' due to the incorporation of a large proportion of adjusted, non-site-specific data (van Dam et al 2019).

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 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. The knowledge needs for contaminants are shown in Table 3.

Table 3 Key Knowledge Needs for contaminants (including copper and zinc)

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?

6. References

ANZG 2018. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Australian and New Zealand Governments and Australian state and territory governments, Canberra ACT, Australia. Available at www.waterquality.gov.au/anz-guidelines

Canadian Council of Ministers of the Environment (CCME) 2018. Scientific criteria document for the development of the Canadian water quality guidelines for the protection of aquatic life: zinc. Canadian Council of Ministers of the Environment, Winnipeg, MB.

Garde M 2013. *Closure Criteria Development — Cultural*. Commercial-in-Confidence report from GAC to the Ranger mine Closure Criteria Working Group. Darwin 160.

Iles M 2004. *Water quality objectives for Magela Creek — revised November 2004*. Internal Report 489, Supervising Scientist, Darwin.

Iles M & Humphrey C 2014. *Draft water quality closure criteria considerations for Pit 3 tailings application: Technical aspects*. Ranger Minesite Technical Committee Water and Sediment Technical Working Group, Darwin.

Trenfield M, Pease C, Walker S, Humphrey C, van Dam R, Markich S & Harford A. Assessing the chronic toxicity of aquatic contaminant mixtures and validating the protectiveness of individual water quality guideline values. In review. *Ecotoxicology and Environmental Safety*.

Turner K & Jones D 2010. Review of solute selection for water quality and bioaccumulation monitoring. In *ERISS research summary 2008–2009,* ed Jones D & Webb A, Supervising Scientist Report 201, Supervising Scientist, Darwin, pp. 66–72.

Appendix: Evidence and further details for copper and zinc toxicity

Copper

There is comprehensive literature reporting the toxicity of copper (Cu) and the key environmental modifying factors that affect its toxicity, especially water hardness, pH and DOC (De Schamphelaere & Janssen 2004, Brix et al. 2017). Applying the results of these studies to the water quality of the creeks surrounding the Ranger mine (low hardness, pH and DOC) indicates higher Cu bioavailability and, hence, higher toxicity in these local waters compared to most freshwater systems (De Schamphelaere & Janssen 2004, Brix et al. 2017), although algal species appear to be less sensitive to Cu at low pH (Wilde et al. 2006). Researchers have developed models that adjust water quality guideline values for varied water quality conditions, and some are used by regulatory authorities (USEPA 2007). However, these models are not validated for the water quality conditions of Magela and Gulungul creeks. Copper also adsorbs particularly strongly to suspended sediment (Bradl 2004), accounting for the high total background concentrations of Cu relative to dissolved concentrations, suggesting that Cu leaving the mine site via surface waters may be associated with suspended sediments. For the data available for Magela Creek, the median concentration of Cu values is 0.2 µg/L (<0.45 µm filtered fraction), with 5th and 95th percentiles of 0.1 and 0.5 µg/L, respectively (data from combined upstream and downstream data from SSB samples over the 2002–2018 period, *n* = 714).

Early local toxicity data generated for Cu in synthetic creek water (Franklin et al. 2000, 2002, Markich & Camilleri 1997, Riethmuller et al. 2000, Williams et al. 1991) were not applicable as the test water lacked DOC, and so represented relatively high bioavailable Cu, with associated enhanced Cu toxicity (Al-Reasi et al. 2012).

More recently (over the dry season of 2020), additional chronic toxicity data were generated for Cu using six local species in Magela Creek water (collected from Bowerbird Billabong, Table A1), following the methods set out in Trenfield et al. (2020). Exposure conditions were characteristic of the slightly acidic, extremely soft, sandy streams of this region: pH 6.1 ± 0.5, electrical conductivity 19 ± 6 µS/cm, water temperature 26-30°C (species-specific), dissolved organic carbon 2.2 ± 1 mg/L, hardness 3 ± 1 mg/L ($CaCO_3$), and alkalinity 3.5 ± 2 mg/L ($CaCO_3$).

Toxicity data for a seventh species, a local mussel, *Velesunio angasi* (Kleinhenz 2019), were also included in the derivation of the GV, with exposure conditions falling within the ranges specified above. The original toxicity data for *V. angasi* were reported as an acute lethal 50% effect concentration (LC50) value of 6.6 µg/L. This value was converted to a chronic 10% effect concentration (EC10 = 1.7 µg/L, Table A1), using an acute to chronic conversion ratio (ACR of 4.0). This ACR was derived following the guidelines set out in Warne et al. (2018) and Batley et al (2014), by calculating the geomean of all ACRs available for Cu and mussels (March et al. 2007, Wang et al. 2007). A Species Sensitivity Distribution was produced by fitting a log normal distribution to the data listed in Table A1 (ShinyApp tool, Dalgarno 2018). The concentration of Cu calculated to protect 99% of species (and the associated 95% confidence limits) was 0.5 µg/L (0.2-1.6).

Table A1 Toxicity data for copper using local species in Magela Creek water

Species	EC10 Cu (µg/L)
Chlorella sp.	1.6
Lemna aequinoctialis	5.5
Hydra viridissima	2.3
Moinodaphnia macleayi	1.0
Amerianna cumingi	3.7
Mogurnda mogurnda	8.2
Velesunio angasi[a]	1.7

[a] Copper data reported by Kleinhenz (2019)

Zinc

There is comprehensive global literature reporting the toxicity of zinc (Zn) and the key environmental modifying factors that affect toxicity, especially water hardness and pH (Bradley & Sprague 1985, Wilde et al. 2006), DOC and humic substances (De Schamphelaere et al. 2005, Koukal et al. 2003), and suspended sediment (Bradl 2004). Applying the results of these studies to the water quality of the creeks surrounding the Ranger mine (low hardness, pH and DOC) suggests Zn toxicity would be accentuated in these local waters. For the data available for Magela Creek, the median concentration of Zn is 0.25 µg/L (<0.45 µm filtered fraction), with 5th and 95th percentiles of 0.25 and 1.5 µg/L, respectively (data from combined upstream and downstream data from SSB samples over the 2002–2018 period, *n* = 540).

Only very limited local toxicity data had been generated for Zn, i.e. exposure of hydra to Zn in synthetic creek water (Wilde et al. 2006). These data were generated in test waters that lacked DOC, thereby representing conditions for high Zn bioavailability and, hence, higher Zn toxicity (De Schamphelaere et. al. 2005).

More recently (over the dry season of 2020), chronic toxicity data were generated for Zn and local species in MCW (collected from Bowerbird Billabong) following the methods set out in Trenfield et al. (2020). The initial approach to derive a site-specific GV was based on data generated for six local species (species 1-6 listed in Table A2). A Species Sensitivity Distribution (SSD) was produced by fitting a log-normal distribution to the data (refer to Supervising Scientist Branch Technical Advice #030). The concentration of Zn calculated to protect 99% of species (and the associated 95% confidence limits) was 6.5 µg/L Zn (2-10.5 µg/L). However, the resulting SSD model-fit was poor, and the site-specific GV considered to be of low reliability based on the national classification system outlined in Warne et al. (2018).

Table A2 Chronic EC10 (µg/L Zn) values derived for seven local species and 22 additional species exposed to zinc

#	Local species	Chronic Endpoint	Zn (µg/L)	Converted EC10	Reference
1	*Chlorella* sp.	EC10	286		This study
2	*Lemna aequinoctialis*	EC10	320		This study
3	*Hydra viridissima*	EC10	53		This study
4	*Moinodaphnia macleayi*	EC10	40		This study
5	*Amerianna cumingi*	EC10	27		This study
6	*Mogurnda mogurnda*	EC10	29		This study
7	*Velesunio angasi*	LC50[a]	52	21	This study
	Additional species		**Original EC**	**Corrected EC10[b]**	
8	*Bufos boreas*	NOEC	172	52	Davies & Brinkman (1999)
9	*Acipenser transmontanus*	LC20	102	23	Vardy et al. (2011)
10	*Cottus bairdi*	NOEC	37	13	Besser et al. (2007)
11	*Oncorhynchus clarkii*	NOEC	294	86	Brinkman & Hansen (2004)
12	*Oncorhynchus mykiss*	EC10	130	37	Mebane et al. (2008)
13	*Pimephales promelas*	NOEC	129	36	Norberg-King (1989)
14	*Prosopium williamsoni*	IC20	422	63	Brinkman & Vieira (2008)
15	*Salmo trutta*	NOEC	76	28	Kallqvist et al. (2003)
16	*Salvelinus fontinalis*	NOEC	190	92	Davies et al. (2002)
17	*Hyalella azteca*	NOEC	42	14	Borgmann et al. (1993)
18	*Paratya australiensis*	LC50[c]	100	11	Bacher & O'Brien (1990)
19	*Hydropsyche betteni*	NOEC	5400	244	Balch et al. (2000)
20	*Ceriodaphnia dubia*	NOEC	13	3	Cooper et al. (2009)
21	*Ceriodaphnia reticulata*	NOEC	90	7	Carlson et al. (1986)
22	*Daphnia magna*	EC10	80	4	Heijerick et al. (2003)
23	*Dreissena polymorpha*	NOEC	517	63	Kraak et al. (1994)
24	*Echyridella menziesii*	EC20	168	120	Clearwater et al. (2014)
25	*Lampsilis siliquoidea*	IC10	55	37	Wang et al. (2010)
26	*Physa gyrina*	NOEC	570	205	Nebeker et al. (1986)
27	*Potamopyrgus jenkinsi*	NOEC	61	4	Dorgelo et al. (1995)
28	*Lymnaea stagnalis*	EC10	508	65	De Schamphelaere et al. (2010)
29	*Pseudokirchneriella subcapitata*	EC10	139	14	De Schamphelaere et al. (2005)

[a] This acute value was converted to a chronic value using an ACR (2.5) specific to mussels published by Wang et al. (2010).

[b] Original ECs have been corrected to a hardness of 5 mg/L $CaCO_3$, pH 6.4 and dissolved organic carbon of 1.5 mg/L using the relationship for *Oncorhynkuss mykiss* (rainbow trout) with zinc toxicity reported by CCME (2018):

$$\text{Standardized EC}_{10} = \exp[\ln(\text{EC}_{10\text{meas}}) - \text{DOC}_{\text{slope}}(\ln[\text{DOC}_{\text{meas}}] - \ln[\text{DOC}_{\text{target}}]) - \text{pH}_{\text{slope}}(\text{pH}_{\text{meas}} - \text{pH}_{\text{target}}) - \text{hardness}_{\text{slope}}(\ln[\text{hardness}_{\text{meas}}] - \ln[\text{hardness}_{\text{target}}])]$$

[c] This is a chronic LC50. It was first corrected as specified above (corrected to an LC50 = 30 µg/L) and then converted to an EC10 by dividing the LC50 by 5 (following procedure outlined in ANZG (2018))

Following current best-practice and to improve on the initial site-specific SSD model, toxicity estimates for both local species and additional non-local species were combined for guideline value derivation (Table A2). The toxicity estimates derived from non-local species were adjusted to local water quality conditions using a published model (CCME 2018). This approach was deemed the most appropriate because of the strong international research basis for Zn underpinning the relationships between biological effects and key toxicity modifying factors (i.e. pH, hardness and DOC). This “site-adapted” Guideline Value approach (van Dam et al. 2019) significantly improved the fit and reliability of the Species Sensitivity Distribution (Supervising Scientist Branch 2020).

Data for an additional 22 non-local species (Table A2) were sourced from the literature and quality-checked using the guidance of Warne et al. (2018). The selection of toxicity estimates also followed the advice of Warne et al. (2018), i.e. where there were multiple candidate values for a species, the lowest value has been used rather than a geomean of the values. The values were not combined and averaged due to the differences in endpoint and exposure duration across the studies. However, Warne et al., (2018) recommended that NOECs be excluded if more accurate toxicity estimates for ≥8 species from ≥5 taxonomic groups are available. This advice was not followed and NOECs were included in the dataset as they constituted 45% the available toxicity estimates and their inclusion also met the “preferred” dataset size of ≥15 data points. Their inclusion improved the modelling and fitting of the SSD. The lowest value was adjusted to the water quality conditions of Magela and Gulungul Creeks, i.e. ~5 mg/L hardness, pH 6.4 and 1.5 mg/L DOC (Table A2), prior to inclusion in the derivation using a Multiple Linear Regression model from CCME (2018). An acute toxicity estimate generated for larvae of a local mussel, *Velesunio angasi*, using methods reported in Tybell (2019), was also included. The acute effect concentration (LC50) was converted to a chronic toxicity estimate (EC10) using an ACR of 2.5 (Wang et al. 2010), for inclusion in the derivation of the GV.

A Species Sensitivity Distribution was produced, using the toxicity estimates from the collective 29 species, by fitting a model-average distribution to the data (Supervising Scientist Branch 2020). The concentration of zinc calculated to protect 99% of species (and the associated 95% confidence limits) was 1.5 µg/L Zn (0.7 – 4.1 µg/L). Based on the preferred sample size ≥15, the use of chronic data, and the adequacy of the fit of the data to the SSD model, this GV would be classified “very high reliability” using the criteria of Warne et al. (2018). However, the modelling relied on 13 NOECs and 75% of the toxicity estimates were adjusted with a model that has not been validated in soft waters. Hence, this guideline value should be only be considered “moderate” reliability. While original data for one of the 29 species were acute, this value was converted with high confidence using a mussel-specific ACR. This single data-point also had little overall influence on the GV. The GV is classified as ‘site-adapted’ rather than ‘site-specific’ due to the incorporation of a large proportion of adjusted, non-site-specific data (van Dam et al 2019).

Additional references

Al-Reasi HA, Smith SD & Wood CM 2012. Evaluating the ameliorative effect of natural dissolved organic matter (DOM) quality on copper toxicity to *Daphnia magna*: improving the BLM. *Ecotoxicology* 21, 524–537.

ANZG 2018. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Australian and New Zealand Governments and Australian state and territory governments, Canberra ACT, Australia. Available at www.waterquality.gov.au/anz-guidelines

Bacher GJ & O'Brien TA 1990. *The sensitivity of Australian freshwater aquatic organisms to heavy metals*. Scientific Series Report 88/018. Victorian Environmental Protection Authority, Melbourne, Victoria, Australia.

Balch GC, Evans RD, Welbourn P & Prairie R 2000. Weight loss and net abnormalities of *Hydropsyche betteni* (caddisfly) larvae exposed to aqueous zinc. *Environmental Toxicology and Chemistry* 19, 3036-3043.

Batley GE, van Dam RA, Warne MS, Chapman JC, Fox DR, Hickey CW & Stauber JL 2014. *Technical rationale for changes to the method for deriving Australian and New Zealand water quality guideline values for toxicants*. Prepared for the Australian Government Standing Council on Environment and Water (SCEW), Canberra.

Besser JM, Mebane CA, Mount DR, Ivey CD, Kunz JL, Greer IE, May TW & Ingersoll CG 2007. Sensitivity of mottled sculpins (*Cottus bairdi*) and rainbow trout (*Oncorhynchus mykiss*) to acute and chronic toxicity of cadmium, copper, and zinc. *Environmental Toxicology and Chemistry* 26, 1657-1665.

Borgmann U, Norwood WP & Clarke C 1993. Accumulation, regulation and toxicity of copper, zinc, lead and mercury in *Hyalella azteca*. *Hydrobiologia* 259, 79-89.

Bradl HB 2004. Adsorption of heavy metal ions on soils and soils constituents. *Journal of Colloid and Interface Science* 277, 1–18.

Bradley RW & Sprague JB 1985. The influence of pH, water hardness and alkalinity on the acute lethality of zinc to rainbow trout (*Salmo gairdneri*). *Canadian Journal of Fisheries and Aquatic Sciences* 42, 731–736.

Brinkman S & Hansen D 2004. Effect of hardness on zinc toxicity to Colorado River cutthroat (*Oncorhynchus clarkii pleuriticus*) and rainbow trout (*Oncorhynchus mykiss*) embryos and fry. Water Pollution Studies. Federal Aid Project F-243-R11. Colorado Division of Wildlife, Fort Collins, CO, USA. Brinkman S, Vieira N. 2008. Water Pollution Studies. Federal Aid Project F-243-R15. Colorado Division of Wildlife, Fort Collins, Colorado.

Brix KV, DeForest DK, Tear L, Grosell M & Adams WJ 2017. Use of Multiple Linear Regression Models for Setting Water Quality Criteria for Copper: A Complementary Approach to the Biotic Ligand Model. *Environmental Science & Technology* 51, 5182–5192.

Carlson AR, Nelson H & Hammermeister D 1986. Evaluation of site-specific criteria for copper and zinc: An integration of metal addition toxicity, effluent and receiving water toxicity. EPA 600/3-86-026. U.S. EPA, Duluth, MN.

Clearwater SJ, Thompson KJ & Hickey CW 2014. Acute toxicity of copper, zinc, and ammonia to larvae (Glochidia) of a native freshwater mussel *Echyridella menziesii* in New Zealand. *Archives of Environmental Contamination and Toxicology* 66, 213-226.

Cooper NL, Bidwell JR & Kumar A 2009. Toxicity of copper, lead, and zinc mixtures to *Ceriodaphnia dubia* and *Daphnia carinata*. *Ecotoxicology and Environmental Safety* 72, 1523-1528.

Dalgarno S 2018. ssdtools: A shiny web app to analyse species sensitivity distributions. Prepared by Poisson Consulting for the Ministry of the Environment, British Columbia. https://bcgov-env.shinyapps.io/ssdtools/

Davies PH & Brinkman S 1999. Water Pollution Studies. Federal Aid Project F-243R-6. Colorado Division of Wildlife, Fort Collins, CO, USA.

De Schamphelaere KAC & Janssen CR 2004. Effects of dissolved organic carbon concentration and source, pH and water hardness on chronic toxicity of copper to *Daphnia magna*. *Environmental Science and Technology* 23, 1115–1122.

De Schamphelaere KAC, Lofts S & Janssen CR 2005. Bioavailability models for predicting acute and chronic toxicity of zinc to algae, daphnids, and fish in natural surface waters. *Environmental Toxicology and Chemistry* 24, 1190–1197.

Dorgelo J, Meester H & van Velzen C 1995. Effects of diet and heavy metals on growth rate and fertility in the deposit-feeding snail *Potamopyrgus jenkinsi* (Smith) (Gastropoda: Hydrobiidae). *Hydrobiologia* 316, 199-210.

Franklin NM, Stauber SL, Markich SJ & Lim RP 2000. pH dependent toxicity of copper and uranium to a tropical freshwater alga (*Chlorella* sp.). *Aquatic Toxicology* 48, 275–289.

Franklin NM, Stauber JL, Apte SC & Lim RP 2002. Effect of initial cell density on the bioavailability and toxicity of copper in microalgal bioassays. *Environmental Toxicology and Chemistry* 21, 742–751.

Giles M 1974. *Toxicity studies on aquatic organisms and grass-sedge communities in the Magela Creek area,* Report II, in The Alligator Rivers Area fact-finding study, four AAEC Reports. AAEC, Lucas Heights, NSW.

Hart BT & Davies SHR 1980. *Trace metal complexing capacity of waters in the Magela Creek system, Northern Australia*. Technical Memorandum 15, Caulfield Institute of Technology, Caulfield East, Vic.

Heijerick DG, Janssen CR & Coen WMD 2003. The combined effects of hardness, pH, and dissolved organic carbon on the chronic toxicity of Zn to *D. magna*: Development of a surface response model. *Archives of Environmental Contamination and Toxicology* 44, 210-217.

Holdway DA, Lok K & Semaan M 2001. The acute and chronic toxicity of cadmium and zinc to two hydra species. *Environmental Toxicology* 16, 557–565.

Källqvist T, Rosseland BO, Hytterød S & Kristensen T 2003. Effect of zinc on the early life stages of brown trout (*Salmo trutta*) at different levels of water hardness. Report No. 4687 -2003. Norwegian Institute for Water Research, Oslo, Norway

Kleinhenz LS 2019. *Development of tropical freshwater mussel toxicity tests and an assessment of key contaminants from the Ranger uranium mine.* (Doctor of Philosophy). RMIT, Melbourne.

Koukal B, Gueguen C, Pardos M & Dominik J 2003. Influence of humic substances on the toxic effects of cadmium and zinc to the green alga *Pseudokirchneriella subcapitata*. *Chemosphere* 53, 953—961.

Kraak MHS, Wink YA, Stuijfzand SC, Jong MCBD, Degroot CJ & Admiraal W 1994. Chronic ecotoxicity of Zn and Pb to the zebra mussel *Dreissena polymorpha*. *Aquatic Toxicology* 30, 77-89.

March FA, Dwyer FJ, Augspurger T, Ingersoll CG, Wang N & Mebane CA 2007. An evaluation of freshwater mussel toxicity data in the derivation of water quality guidance and standards for copper. *Environmental Toxicology and Chemistry* 26, 2066-2074.

Markich S & Jeffree RA 1994. Absorption of divalent trace metals as analogues of calcium by Australian freshwater bivalves: an explanation of how water hardness reduces metal toxicity. *Aquatic Toxicology* 29, 257–290.

Markich S & Camilleri C 1997. *Investigation of metal toxicity to tropical biota: Recommendations for revision of the Australian water quality guidelines*. Supervising Scientist Report 127, Supervising Scientist, Canberra.

Mebane CA, Hennessy DP & Dillon FS 2008. Developing acute-to-chronic toxicity ratios for lead, cadmium, and zinc using rainbow trout, a mayfly, and a midge. *Water Air Soil Pollution* 188, 41-66.

Nebeker AV, Stinchfield A, Savonen C & Chapman GA 1986. Effects of copper, nickel and zinc on three species of Oregon freshwater snails. *Environmental Toxicology and Chemistry* 5, 807-811.

Norberg-King TJ. 1989. An evaluation of the fathead minnow 7-day subchronic test for estimating chronic toxicity. *Environmental Toxicology and Chemistry* 8, 1075-1089.

Peuranen S, Vuorinen PJ, Vuorinen M & Hollender A 1994. The effects of iron, humic acids and low pH on the gills and physiology of brown trout (*Salmo trutta*). *Annales Zoologici Fennici* 31, 389–396.

Riethmuller N, Markich S, Parry DL & van Dam RA 2000. *The effect of true water hardness and alkalinity on the toxicity of Cu and U to two tropical Australian freshwater organisms*. Supervising Scientist Report 155, Supervising Scientist Division, Darwin, Northern Territory, Australia.

Schwartz ML, Curtis PJ & Playle RC 2004. Influence of natural organic matter source on acute copper, lead and cadmium toxicity to rainbow trout (*Oncorhynchus mykiss*). *Environmental Toxicology and Chemistry* 23, 2889–2899.

Supervising Scientist Branch 2020. Technical Advice #30. Site-adapted guideline value for zinc. Darwin, Northern Territory, Australia.

Trenfield M, Pease C, Walker S, Mooney T, Tybell L, Humphrey C, van Dam RA & Harford A 2020. Standardised chronic toxicity test protocols and culturing methods for a suite of tropical freshwater species. *Australasian Bulletin of Ecotoxicology and Environmental Chemistry* Volume 6, 1-80.

USEPA 1985. *Ambient water quality criteria for copper — 1984*. EPA440/5-84-031. Office of Water Regulations and Standards, Criteria and Standards Division, Washington, DC.

USEPA 2007. *Aquatic life ambient freshwater quality criteria — copper*. EPA 822-R-07-001. Office of Water Regulations and Standards, Criteria and Standards Division, Washington, DC.

van Dam RA, Hogan AC, Harford AJ & Humphrey CL 2019. How specific is site-specific? A review and guidance for selecting and evaluating approaches for deriving local water quality benchmarks. *Integrated Environmental Assessment and Management* 15, 683-702.

Wang N, Ingersoll CG, Hardesty DK, Ivey CD, Kunz JL, May TW, Dwyer JF, Roberts AD, Augspurger T & Kane CM 2007. Acute toxicity of copper, ammonia, and chlorine to glochidia and juveniles of freshwater mussels (Unionidae). *Environmental Toxicology and Chemistry* 26, 2036-2047.

Wang N, Ingersoll CG, Ivey CD, Hardesty DK, May TW, Augspurger T, Roberts AD, van Genderen E & Barnhart MC 2010. Sensitivity of early life stages of freshwater mussels (Unionidae) to acute and chronic toxicity of lead, cadmium and zinc in water. *Environmental Toxicology and Chemistry* 29, 2053-2063.

Warne MS, Batley GE, Van Dam RA, Chapman J, Fox D, Hickey C & Stauber J 2018. *Revised method for deriving Australian and New Zealand water quality guideline* *values for toxicants*. Prepared for the Council of Australian Government's Standing Council on Environment and Water (SCEW). Department of Science, Information Technology and Innovation, Brisbane, Queensland.

Wilde KL, Stauber JL, Markich SJ, Franklin NM & Brown PL 2006. The effect of pH on the uptake and toxicity of copper and zinc in a tropical freshwater alga (Chlorella sp*.). Archives of Environmental Contamination and Toxicology* 51, 174–185.

Williams N, Kool KM & Simpson RD 1991. Copper toxicity to fishes and an extremely sensitive shrimp in relation to a potential Australian tropical mining-waste seep. *International Journal of Environmental Studies* 38, 165–18.