An Australian Government Initiative

Australian & New Zealand GUIDELINES FOR FRESH & MARINE WATER QUALITY

Toxicant default guideline values for aquatic ecosystem protection

Gallium in marine water

Technical brief

October 2026

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This publication is available at waterquality.gov.au/anz-guidelines/guideline-values/default/water-quality-toxicants/toxicants.

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Acknowledgements
These default guideline values (DGVs) are third party DGVs that were funded by Rio Tinto Aluminium and Queensland Alumina Limited and derived by Dr Rick van Dam, WQadvice, Torrensville, South Australia. The DGVs were peer reviewed by 2 anonymous reviewers and by 2 jurisdictional technical advisers, Dr Paula Sardina and Dr Paul Leahy, Victorian Environment Protection Authority, and 2 contracted technical advisors, Dr Rick van Dam and Dr Melanie Trenfield.

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Summary

The DGVs and associated information in this technical brief should be used in accordance with the detailed guidance provided on the Australian and New Zealand Guidelines for Fresh and Marine Water Quality website (www.waterquality.gov.au/anz-guidelines).

Gallium is a trivalent, non-essential metal that is mostly found in association with zinc, germanium and aluminium, and primarily in the mineral germanite. The primary source of gallium for human use is recovery as a by-product of processing bauxite and zinc ores. Gallium is known as a technology-critical element due to its use in semiconductors for integrated circuits, which are used in items such as computers and telecommunications equipment, and in optoelectronic devices such as laser diodes, light-emitting diodes (LEDs) and solar cells. It is also used for numerous medical applications.

The primary source of gallium to marine waters is aeolian (dust) deposition. However, anthropogenic sources, such as those associated with bauxite/aluminium and zinc extraction and processing and semiconductor manufacturing and recycling facilities, can also be significant in localised areas.

Gallium exists in seawater as the strongly hydrolysed hydroxy complex $Ga(OH)_4^-$. Natural background concentrations of gallium in seawater are typically in the hundreds of picograms to nanograms per litre range. However, there is a paucity of published data on nearshore and anthropogenically elevated concentrations of gallium in aquatic ecosystems.

The previous Australian and New Zealand default guideline value (DGV) for gallium in marine water was a low-reliability, indicative interim working level of 18 µg/L. This value was based on a single chronic toxicity value for a freshwater fish, as there were no marine toxicity data available at the time (ANZECC and ARMCANZ 2000). There are now sufficient data on the toxicity of gallium to marine species, particularly for Australasian species, to enable the derivation of improved DGVs compared to those in the ANZECC and ARMCANZ (2000) guidelines. The DGVs reported here build upon gallium marine guideline values derived by van Dam et al. (2018a) and supersede the ANZECC and ARMCANZ (2000) DGV.

Based on the limited available data, the toxicity of gallium to marine species appears to be low. Available chronic toxicity values for marine species ranged from 860 µg/L for the diatom *Ceratoneis closterium* (72-hour IC10 for growth rate; see Glossary and acronyms for definitions) to approximately 6,000 µg/L for the hermit crab *Coenobita variabilis* (6-day EC10 for larval development) and the golden microalga *Tisochrysis lutea* (72-hour NOEC for population growth). Gallium has a low potential to bioaccumulate in aquatic biota and does not biomagnify within the food chain.

Low-reliability DGVs for dissolved gallium in marine waters were derived based on chronic toxicity data for 6 Australasian marine species belonging to 5 taxonomic groups, and a poor fit of the species sensitivity distribution to the toxicity data. The DGVs for 99%, 95%, 90% and 80% species-protection levels are 400 µg/L, 800 µg/L, 1,100 µg/L and 1,700 µg/L, respectively. These DGVs relate to dissolved gallium, operationally defined as the < 0.45 µm-filtered measurement. Low-reliability guideline values are not adequate to assess water quality, but can be used as interim values until more reliable

values are derived; they should always be used in conjunction with other lines of evidence (ANZG 2018).

1 Introduction

Gallium is the 32nd most abundant element and constitutes 0.0005% of the Earth's crust (Gad 2014). It is a trivalent, non-essential metal that is mostly found in association with zinc, germanium and aluminium, and primarily in the mineral germanite (Gad 2014).

Gallium is one of a number of elements that are used in the electronics industry, referred to as technology-critical elements (TCEs) (Gad 2014; Lu et al. 2017; Romero-Freire et al. 2019; Bu-Olayan and Thomas 2020). Gallium (e.g. as gallium arsenide or gallium nitride) is one of the major elements in semiconductors for integrated circuits, which are used in items such as computers and telecommunications equipment, and in optoelectronic devices such as laser diodes, light-emitting diodes (LEDs), solar cells and pressure sensors for touch switches (Kaneko et al. 2007; White and Shine 2016; Lu et al. 2017; Romero-Freire et al. 2019; Royal Society of Chemistry 2022; USGS 2023). It also has medical applications, as radioisotopes for medical imaging, and in chemotherapeutic agents and antimicrobial agents (Kaneko et al. 2007; Gad 2014; White and Shine 2016).

Gallium is typically recovered as a by-product of processing bauxite and zinc ores (Licht et al. 2015; Lu et al. 2017; USGS 2023), during which it is enriched up to approximately 50 mg/kg (White and Shine 2016). Global gallium production in 2022 was estimated to be 550 tonnes, with most of this being produced in China (USGS 2023). Given that the primary source of gallium is bauxite/aluminium and zinc extraction and processing, it is known that gallium is present in elevated concentrations in wastewaters associated with these processes (Shiller and Frilot 1996; Lu et al. 2017; van Dam et al. 2018a). Wastewaters are often discharged to the aquatic environment. This source is likely to be the most significant anthropogenic contribution of gallium to the aquatic environment in Australia. Emissions from activities such as gallium processing and from semiconductor manufacturing and recycling facilities can also represent anthropogenic sources of gallium to the aquatic environment (Licht et al. 2015; White and Shine 2016; Lu et al. 2017). Gallium is considered one of the more potentially environmentally significant metals within a group of approximately 7 'lesser-studied' TCEs (Romero-Freire et al. 2019; Bu-Olayan and Thomas 2020; Batley and Campbell 2022).

Gallium exists in seawater as a strongly hydrolysed hydroxy complex, the $Ga(OH)_4^-$ ion (Savenko and Savenko 2010; Hayes 2019). As the aqueous gallium concentration increases, metastable polynuclear species form, which eventually precipitate as $Ga(OH)_3(s)$ (Batley and Campbell 2022). In seawater, natural background concentrations of gallium are typically in the range of hundreds of picograms to nanograms per litre (Shiller 1998; King 2013; Gad 2014; White and Shine 2016; Romero-Freire et al. 2019). Aeolian (dust) deposition is the main global source of gallium to marine waters, although inputs from river plumes may be important in certain coastal areas (Shiller 1998; King 2013; Romero-Freire et al. 2019). Gallium solubility in seawater is reported to be strongly pH dependent, with solubility being higher at lower and higher pH; at typical seawater pH of 7.8 to 8.2, solubility is reported to range from 9 mg/L to 105 mg/L (being 16 mg/L at pH 8.1) (Savenko and Savenko 2010).

Despite concerns over the past 20 years about the potential for TCEs such as gallium to enter aquatic ecosystems (e.g. Yang and Chen 2002; Onikura et al. 2005; Romero-Freire et al. 2019), there are limited published data on anthropogenically elevated concentrations of gallium in aquatic ecosystems. There are some reports of elevated concentrations in lake sediments in Sweden

(~160 mg/kg) as a result of historical industrial activity (White and Shine 2016), and in groundwater (8–41 µg/L) (Chen 2006) and coastal surface waters (0.8–1.2 µg/L) (Hsu et al. 2011) in Taiwan, associated with semiconductor, electronics and optoelectronic manufacturing facilities. There are limited published data on coastal/marine gallium concentrations for Australia and New Zealand. Some data exist in relation to the Gove alumina refinery in the Northern Territory. Gallium concentrations in the refinery wastewater discharge were 1–2 µg/L (Harford et al. 2011; Negri et al. 2011); however, receiving water column concentrations would have been lower than this upon immediate dispersion and dilution of the discharge. For the same refinery, gallium concentrations in marine sediments (total extractable metal) and porewater near the discharge location were 30–50 mg/kg and 1–2 µg/L, respectively, dropping to 20 mg/kg and ≤ 0.1 µg/L at reference sites 1–2 km offshore (Cornall et al. 2013; Neave et al. 2013).

Gallium concentrations in marine biota have been measured for numerous species and geographical locations, and were reviewed by Romero-Freire et al. (2019). A brief summary is provided here: 20 to 1,500 ng/g (parts per billion) in mussels and clams from the Mediterranean; 2 ± 1 ng/g in 32 fish species from France; 7 ± 12 ng/g in seafood from France; 9 to 469 ng/g in liver and < 1 to 104 ng/g in muscle in fish from Malaysian coastal waters; and 5 ± 2 ng/g and 3 ± 4 ng/g in liver samples of 2 dolphin species from Brazil. Romero-Freire et al. (2019) did not specify whether the reported concentrations were expressed as dry or wet weight. Gallium appears to be proportionally distributed throughout body tissues. Karlsson et al. (2002) reported a bioaccumulation factor (BAF) for gallium in marine fish of 700 (i.e. log BAF = 2.8), which indicates that gallium does not have a high potential to bioaccumulate. Additionally, in analysing a range of trace elements in a pelagic Arctic marine food web, including primary producers, invertebrates, fish, seabirds and mammals, Campbell et al. (2005) found no relationship between the concentration of gallium and trophic position, indicating that gallium was not biomagnified through the food web. Thus, gallium is unlikely to represent a concern for secondary consumers.

There are very few existing formal water quality guideline values for gallium in marine water. ANZECC and ARMCANZ (2000) reported a low-reliability, indicative interim working level for marine water of 18 µg/L. However, this was based on a single chronic toxicity value for the freshwater rainbow trout (*Oncorhynchus mykiss*), as there were no toxicity data available at the time for marine species. Over the past 2 decades, the toxicity of gallium to numerous marine species has been studied, and although the dataset is still small compared to many other metals, it is sufficient to derive improved default guideline values (DGVs) for marine water for Australia and New Zealand. Many of the existing data are from Australian studies of Australasian species. The updated DGVs reported here build upon the guideline values for gallium derived by van Dam et al. (2018a) and supersede the ANZECC and ARMCANZ (2000) low-reliability, indicative interim working level value.

2 Aquatic toxicology

2.1 Mechanisms of toxicity

Gallium is considered a non-essential metal. Although little is known about its mechanisms of toxicity in aquatic species, there is a lot of information available in the literature on mammalian toxicology. Based on this literature, gallium can affect various biochemical and physiological functions, such as

interfering with calcium and iron uptake, transport and metabolism; inhibiting protein synthesis; inhibiting the heme pathway enzyme aminolevulinic acid dehydratase; and inhibiting DNA synthesis via its action on ribonucleotide reductase (Yang and Cheng 2002; Lemire et al. 2010; Gad 2014). In living systems, gallium acts as an iron mimic, thus displacing this element in critical molecules and interfering with related processes (Lemire et al. 2010). Gallium exposure has been reported to cause significant oxidative stress in organisms (Lemire et al. 2010; Chang et al. 2017).

Yang and Chen (2002) assessed the effects of gallium on a range of serum biochemistry parameters in the common carp, *Cyprinus carpio*, and found that the liver and kidneys were target organs. The authors also found morphological changes to erythrocytes, suggesting that interference with respiration is an additional response to gallium exposure. However, underlying mechanisms of toxicity were not elucidated. Gallium has also been reported to be an immunosuppressant at high concentrations (> 3,500 µg/L) and, potentially, an immunostimulant at low concentrations (3.5 µg/L) in *C. carpio* (Betoulle et al. 2002).

2.2 Toxicity

There are limited available gallium toxicity data for marine species. The first available acute toxicity data were reported up to 20 years ago, with chronic toxicity data not reported for another 10 years thereafter.

Onikura et al. (2005) assessed the acute toxicity of gallium to 3 brackish and marine species as 26–31 parts per thousand salinity, reporting a 96-hour LC50 of 12,760 µg/L for a mysid shrimp, *Americamysis bahia*; a 24-hour LC50 of 11,480 µg/L for a rotifer, *Brachionus plicatilis*; and a 48-hour LC50 of 52,780 µg/L for the brine shrimp *Artemia salina*. Nguyen et al. (2020) assessed the acute toxicity of gallium arsenide and gallium oxide to methanogenic archaea (measured by inhibition of methanogenic activity) and the marine bacterium *Aliivibrio fischeri* (measured by the Microtox® assay). Gallium oxide was not acutely toxic to the microorganisms, while toxicity of gallium arsenide was attributed to arsenic.

Based on the limited available literature, marine species are insensitive to chronic gallium exposure, with toxicity typically reported near or above 1 mg/L. The diatom *Ceratoneis closterium* (formerly *Nitzschia closterium*) is the most sensitive species, with a 72-hour IC10 (growth rate) of 860 µg/L (Harford et al. 2011), followed by the coral *Acropora tenuis*, with an 18-hour IC10 (metamorphosis) of 1,160 µg/L (Negri et al. 2011). Negri et al. (2011) also reported an IC10 of 3,205 µg/L for *A. tenuis* based on 18-hour fertilisation. Other species appear to be even more tolerant to chronic gallium exposure, with toxicity values ranging from 3,840 µg/L (96-hour EC10 for growth rate) for the gastropod *Nassarius dorsatus* (Trenfield et al. 2016), to 6,010 µg/L (144-hour EC10 for larval development) for the hermit crab *Coenobita variabilis* (van Dam et al. 2018b). The toxicity of gallium to the barnacle *Amphibalanus amphitrite* fell within the range of reported toxicity data, with a 96-hour EC10 (larval development) of 5,070 µg/L (van Dam et al. 2016). No effects were observed on the growth of the golden microalga *Tisochrysis lutea* (formerly *Isochrysis galbana*) up to a gallium concentration of 6,000 µg/L (Trenfield et al. 2015). Notably, all the previously mentioned chronic toxicity data for marine species are for Australasian (sub)tropical species. There are no chronic toxicity data for temperate marine species, thus precluding the ability to compare the sensitivity of temperate and (sub)tropical species.

3 Factors affecting toxicity

Knowledge about the factors that affect the toxicity of gallium to aquatic species is limited. This is likely due to the lack of attention that the aquatic toxicity of gallium has received, and the generally low aquatic toxicity of gallium reported to date.

Gallium will bind to functional groups on dissolved organic carbon (DOC) (Hagvall et al. 2014; Kouhail et al. 2020); however, the ecotoxicological significance of this has not been studied. Tipping and Filella (2019) presented calculated speciation results for gallium and other TCEs, which suggested that most gallium in seawater would be bound to hydroxide ions rather than DOC. Thus, DOC may not be a significant toxicity-modifying factor for gallium in seawater. In contrast, under certain freshwater conditions (e.g. acidic, soft waters), up to 100% of gallium was calculated to be bound to DOC (Tipping and Filella 2019), although Shiller and Frilot (1996) found gallium to not be complexed by organic ligands (at pH 6.8).

The only toxicity-modifying factor that has been assessed for gallium toxicity is salinity. Onikura et al. (2005) found that increasing salinity reduced the acute toxicity of gallium to *A. salina*, with 48-hour LC50s of approximately 1 mg/L, 4 mg/L, 11 mg/L, 19 mg/L and 53 mg/L at 3.3, 5.9, 10.1, 17.7 and 31 PSU, respectively. However, *A. salina* is a saline to hyper-saline species that typically does not perform well at low salinities (e.g. Wasonga and Olendi 2018). Thus, at least some of the higher sensitivity to gallium at lower salinities reported by Onikura et al. (2005) may have been due to the additional stress of low salinity. Ideally, the effect of salinity on gallium toxicity should be assessed using species with a wide range of salinity tolerances.

As other potential toxicity-modifying factors such as pH and water hardness are typically less variable in seawater than in freshwater, their effects on gallium bioavailability and toxicity are not relevant for marine water.

4 Default guideline value derivation

The DGVs were derived in accordance with the method described in Warne et al. (2018), except that the shinyssdtools software (version 0.2.0) (Dalgarno 2018) was used, and the DGVs were rounded to the appropriate number of significant figures according to the guidance in ANZG (2018).

4.1 Toxicity data used in derivation

Gallium toxicity data for marine species that were compiled by van Dam et al (2018a) were used as the base dataset for deriving DGVs. Additionally, a comprehensive literature search was undertaken using Google Scholar and the United States Environmental Protection Agency ECOTOX database (US EPA 2021) to identify additional toxicity data for gallium.

In total, marine toxicity data for gallium were available for 9 species from 6 taxonomic groups (one diatom, one golden microalga, one gastropod mollusc, one cnidarian, one rotifer and 4 crustaceans). Of these, chronic toxicity data were available for 6 species from 5 taxonomic groups, and acute toxicity data for 3 species from 2 taxonomic groups. All data passed the quality assessment and

screening processes prescribed by Warne et al. (2018). All chronic toxicity data were based on measured dissolved (< 0.45 µm-filtered) gallium concentrations, while the acute toxicity data appeared to be based on nominal gallium concentrations.

The chronic toxicity dataset comprised all the data compiled by van Dam et al. (2018a) and additional data as described in section 2.2. Briefly, the data ranged from a 72-hour IC10 (growth rate) of 860 µg/L for the diatom *C. closterium* (Harford et al. 2011) to a 144-hour EC10 (larval development) of 6,010 µg/L for the hermit crab *C. variabilis* (van Dam et al. 2018b). All data were from (sub)tropical marine species, although at least 4 of the species (*C. closterium*, *T. lutea*, *N. dorsatus* and *A. amphitrite*) have broader distributions that extend into temperate zones. For the coral *A. tenuis*, the IC10 based on 18-hour metamorphosis (1,160 µg/L) was lower than, and hence, selected in favour of, the IC10 based on 18-hour fertilisation (3,205 µg/L) (Negri et al. 2011). For all other species, there was only one negligible effect value available for only one endpoint; thus, no additional data selection steps (e.g. selecting lowest value, calculating geometric mean) were necessary. For the golden microalga *T. lutea*, no effects were observed up to and including the highest tested concentration (Trenfield et al. 2015); therefore, the highest test concentration (6,000 µg/L) was treated as the NOEC for this species. This is considered acceptable according to the derivation method (Warne et al. 2018). The 96-hour exposure duration for the gastropod *N. dorsatus* growth test reported by Trenfield et al. (2016) would typically be considered an acute exposure duration. However, Warne et al. (2018) recognise that the typical acute/chronic test classification predominantly applies to temperate species and, as tropical species may experience much faster early development and growth and reproduction rates, chronic toxicity tests using tropical organisms may be of considerably shorter duration than those for temperate species. As *N. dorsatus* is a tropical species, the 96-hour growth response was accepted as an estimate of chronic toxicity.

There were sufficient chronic toxicity data to meet the minimum criterion for deriving DGVs of at least 5 species from at least 4 taxonomic groups (Warne et al. 2018). However, Warne et al. (2018) acknowledge that the minimum criterion is sub-optimal and encourage the inclusion of data for more species where possible, particularly if doing so will result in greater taxonomic representation and higher reliability of DGVs. Consequently, the effect of including the 3 acute toxicity values (described in section 2.2), following their conversion to chronic equivalent negligible effect data, was assessed (Appendix A). The acute LC50s were divided by a default acute-to-chronic ratio (ACR) of 10, as it was not possible to develop gallium-specific ACRs for any of the species. As shown in Appendix A, although the inclusion of the converted acute values resulted in data for 3 more species and one more taxonomic group, the fit of the species sensitivity distribution (SSD) was still poor and it did not improve the reliability of the DGVs. Therefore, only the chronic toxicity data were included in the final dataset.

The chronic toxicity dataset was checked for bi-modality; however, due to the very small sample size (n = 6), not all the formal modality assessment steps recommended by Warne et al. (2018) were informative. As gallium exhibits multiple mechanisms of toxicity targeting processes that are common among all living organisms (e.g. calcium uptake, iron uptake, protein synthesis, DNA synthesis), a bi-modal toxicity relationship is not expected. Consequently, all the chronic toxicity data were used in the final dataset.

The final dataset comprised chronic toxicity data for 6 species from 5 taxonomic groups, including one diatom, one golden microalga, one gastropod mollusc, one cnidarian and 2 crustaceans. The toxicity data included 3 EC10 values, 2 IC10 values and one NOEC value. A summary of the toxicity data used to derive the DGVs is provided in Table 1. Further details on the data that passed the quality assessment and screening process and were used to derive the DGVs are presented in Appendix B. Details of the data quality assessment and the data that passed the quality assessment are provided as supporting information.

Table 1 Summary of chronic toxicity values used to derive default guideline values for dissolved gallium in marine water

Taxonomic group	Species	Life stage	Exposure duration (hours)	Toxicity measure[a] (endpoint)	Final toxicity value (µg/L)
Diatom	*Ceratoneis closterium*[b,d]	Log phase	72	IC10 (growth rate)	860
Golden microalga	*Tisochrysis lutea*[b,e]	Log phase	72	NOEC (growth rate)	6,000
Gastropod mollusc	*Nassarius dorsatus*[b]	Larva	96	EC10 (growth rate)	3,840
Crustacean (barnacle)	*Amphibalanus amphitrite*[b]	Nauplius (larva)	96	EC10 (larval development)	5,070
Crustacean (crab)	*Coenobita variabilis*[c]	Zoea (larva)	144	EC10 (larval development)	6,010
Cnidarian (coral)	*Acropora tenuis*[c]	Larva	18	IC10 (metamorphosis)	1,160

[a] The measure of toxicity being estimated/determined. EC10: 10% effect concentration; IC10: 10% inhibition concentration; NOEC: no-observed-effect concentration.

[b] (Sub)tropical species with distribution also extending into temperate zones.

[c] (Sub)tropical species.

[d] Formerly *Nitzschia closterium*.

[e] Formerly *Isochrysis galbana*.

4.2 Species sensitivity distribution

Figure 1 shows the cumulative frequency (species sensitivity) distribution (SSD) of the 6 marine chronic toxicity values for gallium reported in Table 1. The SSD was plotted using shinyssdtools software (version 0.2.0). The model was judged to provide a poor fit to the data (Figure 1). Further details on the SSD-fitting process are provided in Appendix C.

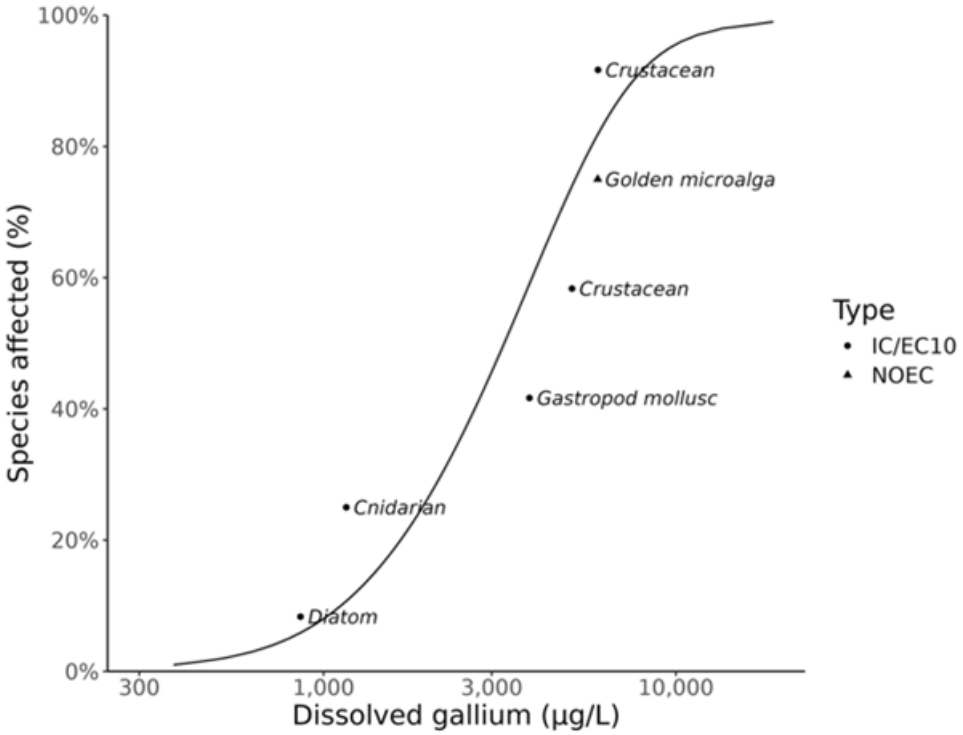


Figure 1 Species sensitivity distribution for dissolved gallium in marine water

4.3 Default guideline values

It is important that the DGVs and associated information in this technical brief are used in accordance with the detailed guidance provided on the Australian and New Zealand Guidelines for Fresh and Marine Water Quality website (www.waterquality.gov.au/anz-guidelines).

Table 2 shows the DGVs for 99%, 95%, 90% and 80% species protection for dissolved gallium in marine water. The uncertainty associated with the DGVs dictated that the 99% and 95% species-protection DGVs should only be reported to one significant figure, while the 90% and 80% species-protection DGVs could be reported to 2 significant figures (Appendix D). The DGVs relate to dissolved gallium, operationally defined as the < 0.45 µm-filtered measurement. Although the DGVs were derived based on data primarily for (sub)tropical species at (sub)tropical temperatures, the DGVs can be considered relevant to both temperate and tropical marine waters until new data demonstrate otherwise. Guidance on the application of DGVs to estuarine waters is provided in ANZG (2018). Further information on the application of the DGVs is provided in section 4.4.

Table 2 Toxicant default guideline values for dissolved gallium in marine water, with low reliability

Level of species protection (%)	DGV for gallium in marine water (µg/L)[a]
99	400
95	800
90	1,100
80	1,700

[a] The DGVs were derived using shinyssdtools software (version 0.2.0) and rounded according to the details provided in Appendix D.

Environmental monitoring data for comparison with a DGV must be rounded according to the Australian Standard AS 2706-2003 (Standards Australia 2003) to the number of significant figures in the DGV.

4.4 Reliability classification

The dissolved gallium in marine water DGVs have a low reliability classification (Warne et al. 2018) based on the outcomes for the following 3 criteria:

- sample size – 6 (adequate)
- type of toxicity data – chronic EC10, IC10, NOEC
- SSD model fit – poor.

As recommended in ANZG (2018), low-reliability guideline values are typically not adequate to assess water quality, but can be used as interim values until more reliable values are derived. If used as interim values, they should always be used in conjunction with other lines of evidence. Although the toxicity of dissolved gallium to marine species appears to be low, chronic toxicity data for at least 2 additional marine species would enable the derivation of moderate- or, potentially, high-reliability DGVs.

Glossary and acronyms

Term	Definition
Acute toxicity	A lethal or adverse sub-lethal effect that occurs as the result of exposure to a chemical for a short period of time (relative to the organism's life span). Refer to Warne et al. (2018) for examples of acute exposures.
Acute-to-chronic ratio (ACR)	The species' mean acute value (LC50/EC50) divided by the chronic value (NOEC) for the same species.
Chronic toxicity	A lethal or adverse sub-lethal effect that occurs as the result of exposure to a chemical for a period of time that is a substantial portion of the organism's life span, or an adverse sub-lethal effect on a sensitive early life stage. Refer to Warne et al. (2018) for examples of chronic exposures.
Default guideline value (DGV)	A guideline value recommended for generic application in the absence of a more specific guideline value (e.g. a site-specific value), in the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Formerly known as 'trigger values'.
DOC	Dissolved organic carbon.
EC10 (10% effect concentration)	The concentration of a substance in water or sediment that is estimated to produce a 10% change in the response being measured or a certain effect in 10% of the test organisms, under specified conditions.
EC50 (median effective concentration)	The concentration of a substance in water or sediment that is estimated to produce a 50% change in the response being measured or a certain effect in 50% of the test organisms, under specified conditions.
Endpoint	The specific response of an organism that is measured in a toxicity test (e.g. mortality, growth, reproduction, a particular biomarker).
Guideline value (GV)	A measurable quantity (e.g. concentration) or condition of an indicator for a specific community value below which (or above which, in the case of stressors such as pH, dissolved oxygen and many biodiversity responses) there is considered to be a low risk of unacceptable effects occurring to that community value. Guideline values for more than one indicator should be used simultaneously in a multiple lines of evidence approach.
IC10 (10% inhibition concentration)	The concentration of a substance in water or sediment that is estimated to produce a 10% inhibition in the response being measured in test organisms relative to the control response, under specified conditions.
LC50 (median lethal concentration)	The concentration of a substance in water or sediment that is estimated to be lethal to 50% of a group of test organisms relative to the control response, under specified conditions. The LC50 is usually expressed as a time-dependent value (e.g. 24-hour or 96-hour LC50).
NOEC (no-observed-effect concentration)	The highest concentration of a toxicant used in a toxicity test that does not have a statistically significant ($p > 0.05$) effect on the exposed population of test animals as compared to the controls. The statistical significance is measured at the 95% confidence level.
PC	Protective concentration.
PSU	Practical salinity units.
Species (biological)	A group of organisms that resemble each other to a greater degree than members of other groups and that form a reproductively isolated group that will not produce viable offspring if bred with members of another group.
Species sensitivity distribution (SSD)	A method that plots the cumulative frequency of species' sensitivities to a toxicant and fits a statistical distribution to the data. From the distribution, the concentration that should theoretically protect a selected percentage of species can be determined.

Term	Definition
Technology-critical element (TCE)	A chemical element that is a critical raw material for modern and emerging technologies such as electronics and green energy.
Toxicity	The inherent potential or capacity of a material to cause adverse effects in a living organism.
Toxicity test	The means by which the toxicity of a chemical or other test material is determined. A toxicity test is used to measure the degree of response produced by exposure to a specific level of stimulus (or concentration of chemical) for a specified test period.

Appendix A: assessment of inclusion of converted acute data into the gallium toxicity dataset

Although the minimum dataset criterion for deriving DGVs requires data for at least 5 species from 4 taxonomic groups, the DGV derivation methodology (Warne et al. 2018) also warns that datasets only just meeting this criterion will be sub-optimal. In this case, data for additional species should be sought, particularly if it will result in greater taxonomic representation and higher reliability of DGVs. One approach for increasing dataset size is to supplement the chronic toxicity data with acute toxicity data that have been converted to chronic equivalent negligible effect data. This approach was assessed for gallium to see if it could improve the reliability of the DGVs.

In addition to the gallium chronic toxicity data for 6 marine species from 5 taxonomic groups (see Table 1), acute toxicity data (reported as LC50s) were available for 3 marine species from 2 taxonomic groups (Onikura et al. 2005). Combining the data resulted in a dataset comprising 9 species from 6 taxonomic groups (Table A1). The acute LC50s were divided by a default acute-to-chronic ratio (ACR) of 10, as it was not possible to develop gallium-specific ACRs for any of the species. A species sensitivity distribution (SSD) was fitted to this dataset using shinyssdtools software (version 0.2.0) (Figure A1), and protective concentration (PC) values estimated for 99%, 95%, 90% and 80% species protection.

Table A1 Summary of combined chronic and acute toxicity values used to derive protective concentration values for dissolved gallium

Taxonomic group	Species	Life stage	Exposure duration (hours)	Acute/ chronic	Toxicity measure[a] (endpoint)	Reported toxicity value (µg/L)	Final toxicity value (µg/L)
Diatom	*Ceratoneis closterium*[b]	Log phase	72	Chronic	IC10 (growth rate)	860	860
Golden microalga	*Tisochrysis lutea*[c]	Log phase	72	Chronic	NOEC (growth rate)	6,000	6,000
Rotifer	*Brachionus plicatilis*	≤24-hour-old neonate	24	Acute	LC50	11,480	1,150[d]
Gastropod mollusc	*Nassarius dorsatus*	Larva	96	Chronic	EC10 (growth rate)	3,840	3,840
Crustacean (barnacle)	*Amphibalanus amphitrite*	Nauplius (larva)	96	Chronic	EC10 (larval development)	5,070	5,070
Crustacean (crab)	*Coenobita variabilis*	Zoea (larva)	144	Chronic	EC10 (larval development)	6,010	6,010
Crustacean (mysid)	*Americamysis bahia*	Nauplius (larva)	96	Acute	LC50	12,760	1,280[d]
Crustacean (brine shrimp)	*Artemia salina*	Nauplius (larva)	48	Acute	LC50	52,780	5,280[d]

Taxonomic group	Species	Life stage	Exposure duration (hours)	Acute/ chronic	Toxicity measure[a] (endpoint)	Reported toxicity value (µg/L)	Final toxicity value (µg/L)
Cnidarian (coral)	*Acropora tenuis*	Larva	18	Chronic	IC10 (metamorphosis)	1,160	1,160

[a] The measure of toxicity being estimated/determined. EC10: 10% effect concentration; IC10: 10% inhibition concentration; LC50: median lethal concentration; NOEC: no-observed-effect concentration.

[b] Formerly *Nitzschia closterium*.

[c] Formerly *Isochrysis galbana*.

[d] Acute LC50 data converted to chronic equivalent negligible effect values by dividing by a default acute-to-chronic ratio of 10.

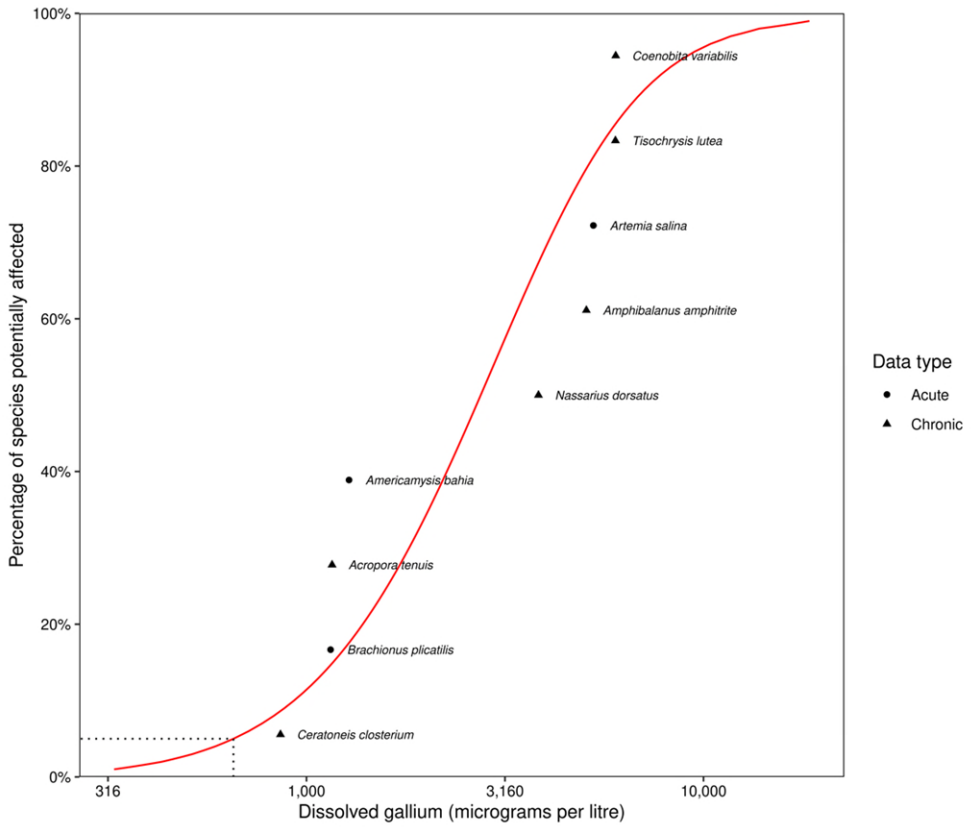


Figure A1 Species sensitivity distribution for dissolved gallium in marine water, chronic and converted acute toxicity data

The resulting PC values for 99%, 95%, 90% and 80% species-protection levels were 330 µg/L, 660 µg/L, 930 µg/L and 1,400 µg/L, respectively. These are similar to the corresponding values estimated from the chronic toxicity dataset SSD (see Table 2). However, the fit of the SSD was still poor (Figure A1). Based on a dataset of 9 chronic and converted acute toxicity values and a poor fit of the SSD, the resulting PC values are considered to be of low reliability, which is the same reliability level as the values estimated from the chronic toxicity dataset SSD. Therefore, as the addition of the acute toxicity values to the chronic toxicity dataset did not improve the reliability of the PC values, only the chronic toxicity data were used to derive the DGVs for gallium in marine water.

Appendix B: toxicity data that passed the screening and quality assessment and were used to derive the default guideline values

Table B1 Summary of toxicity data that passed the screening and quality assurance processes and were used to derive the default guideline values for dissolved gallium in marine water

Taxonomic group	Common name	Scientific name	Life stage	Exposure duration (hours)	Test medium	Test endpoint	Toxicity measure[a]	pH	Temperature (°C)	Toxicity value (µg/L)	Reference
Diatom		*Ceratoneis closterium*[b,d]	Log phase, 10^4 cells/mL	72	0.45 µm-filtered seawater	Growth rate	IC10	8.2	32	860	Harford et al. (2011)
Golden microalga		*Tisochrysis lutea*[b,e]	Log phase, 3 x 10^3 cells/mL	72	Seawater (34.5 PSU)	Growth rate	NOEC	8.2	28	6,000	Trenfield et al. (2015)
Gastropod	Snail	*Nassarius dorsatus*[b]	Larva	96	Seawater (34 ± 1.6 PSU)	Growth rate	EC10	8.4	27	3,840	Trenfield et al. (2016)
Crustacean	Barnacle	*Amphibalanus amphitrite*[b]	Nauplius (larva)	96	Seawater (32.2 ± 0.9 PSU)	Larval development (transition to cyprid)	EC10	8.2	29	5,070	van Dam et al. (2016)
Crustacean	Australian land hermit crab	*Coenobita variabilis*[c]	Zoea (larva)	144	Seawater (33.2 ± 1.7 PSU)	Larval development	EC10	8.2	29	6,010	van Dam et al. (2018b)
Cnidarian	Branched coral	*Acropora tenuis*[c]	Larva	18	0.45 µm-filtered seawater	Metamorphosis	IC10	NR[f]	32	1,160	Negri et al. (2011)

[a] The measure of toxicity being estimated/determined. EC10: 10% effect concentration; IC10: 10% inhibition concentration; NOEC: no-observed-effect concentration.

[b] (Sub)tropical species with distribution also extending into temperate zones.

[c] (Sub)tropical species.

[d] Formerly *Nitzschia closterium*.

[e] Formerly *Isochrysis galbana*.

[f] NR: Not reported.

Appendix C: details of shinyssdtools SSD-fitting process for the gallium toxicity dataset

The SSD software package shinyssdtools (version 0.2.0) uses a model averaging approach to generate an SSD (as described by Fox et al. 2021). Figure C1 shows the full set of default distributions fitted to the gallium marine toxicity dataset, while Table C1 provides the relevant goodness of fit and weighting estimates for each of the distributions. The Log normal – Log normal distribution was weighted zero because it has 5 parameters which, when compared to the dataset of only 6 values, represents severe over-fitting. The final, model-averaged SSD is shown in Figure 1 of the main report.

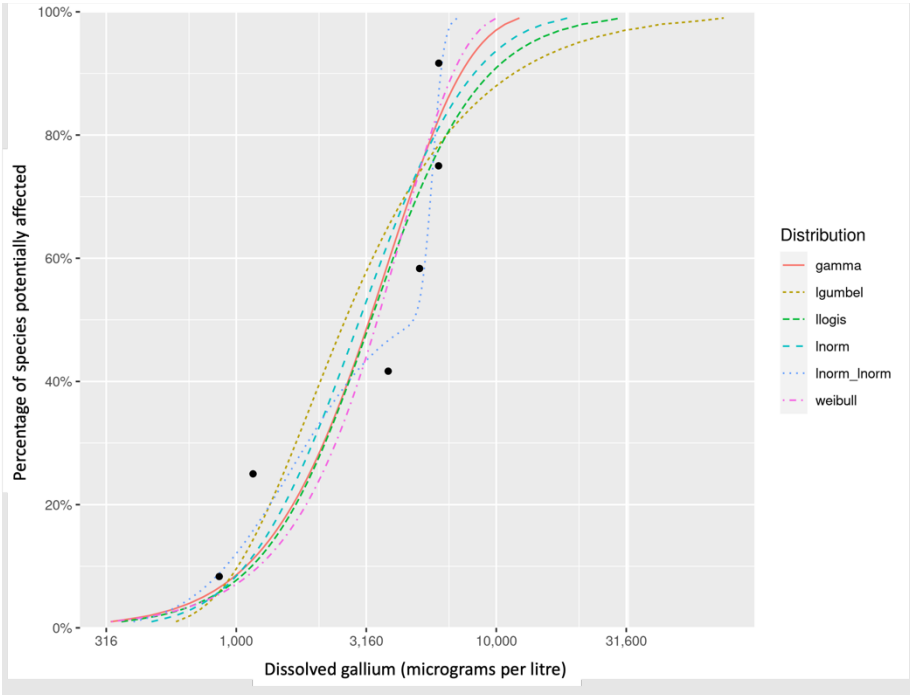


Figure C1 Species sensitivity distributions for the set of 6 default distributions used to model the gallium marine toxicity dataset

Table C1 Goodness of fit and weighting estimates for the 6 default distributions used in model averaging for the gallium marine toxicity dataset

Distribution	Akaike's information criterion (AIC)	Corrected Akaike's information criterion (AICc)	Delta	Weight
Weibull	8.37	12.4	0	0.349
Gamma	8.91	12.9	0.54	0.266
Log normal	9.81	13.8	1.44	0.169
Log logistic	10.4	14.4	2.02	0.127
Log gumbel	11.1	15.1	2.73	0.089
Log normal – Log normal	8.9	Not calculable	Not calculable	0

Appendix D: assessment of significant figures for default guideline values

The number of significant figures to which DGVs are reported is determined by the degree of uncertainty in the values, based on their standard errors, according to the following rule (ANZG 2018):

The significant figure to which a DGV is reported must correspond to the place of the first significant figure in the standard error of the DGV. Where the standard error is greater than the DGV, the DGV must be reported to one significant figure.

For gallium in marine water DGVs, the raw protective concentration (PC) values and their standard errors are shown in Table D1. Standard errors were determined using shinyssdtools software (version 0.2.0) with the default set of distributions (see Appendix C). The standard errors dictated that the 99% and 95% species-protection DGVs are reported to one significant figure, while the 90% and 80% species-protection DGVs are reported to 2 significant figures.

Table D1 Assessment of appropriate number of significant figures for gallium in marine water default guideline values

Level of species protection	Raw PC value (µg/L)	Standard error	Interpretation of significant figures rule	Final DGV (µg/L)
99	375	469	SE > PCx value; therefore, report DGV to one significant figure.	400
95	797	631	First significant figure of the SE at the 10^2 level; therefore, final significant figure for the DGV needs to be at the 10^2 level; corresponds to one significant figure.	800
90	1,120	702	First significant figure of the SE at the 10^2 level; therefore, final significant figure for the DGV needs to be at the 10^2 level; corresponds to 2 significant figures.	1,100
80	1,660	773	First significant figure of the SE at the 10^2 level; therefore, final significant figure for the DGV needs to be at the 10^2 level; corresponds to 2 significant figures.	1,700

DGV: default guideline value; PC: protective concentration; PCx: protective concentration providing 'x' level of species protection (i.e. 99%, 95%, 90%, 80%); SE: standard error.

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