

Environmental transport

Zinc compounds that are emitted to the atmosphere can be transported over long distances via association with particulate matter (ATSDR 2005).

The zinc(2+) ions released from water soluble salts to natural waters are expected to largely partition to sediments, limiting long-range mobility.

In soil, zinc is relatively immobile, except in soils with low pH where there is an increased potential for transport through the soil solution.

Environmental monitoring

Environmental concentrations of metals are usually measured by methods that cannot distinguish between source chemicals. Sources of elevated metal concentrations are generally inferred from exposure scenarios that are likely to influence the affected sites. We note that historical activities may also be a source of zinc contamination at these sites, particularly where facilities have been in operation for a long period of time. The following presents a selection of measured zinc concentrations in the Australian environment and their surrounding context.

Zinc is a naturally occurring element found in the earth's crust (ATSDR 2005). It is present in most natural waters in low concentrations. The ANZ Water Quality Guidelines cite background zinc concentrations in Australia of 0.9 µg/L in fresh water, 0.39–3.8 µg/L in estuaries (ANZECC & ARMCANZ 2000a), and 0.004–0.022 µg/L in marine water (DCCEEW 2021a).

Environmental monitoring studies of Australian coastal areas, including urban harbours, have found zinc concentrations generally below 5.2 µg/L in estuaries and 2.19 µg/L in marine water (Batley 1995; French et al. 2015; Haynes and Johnson 2000). All of these are within default guideline values (8 µg/L for *slightly to moderately disturbed* marine ecosystems at the 95% protection level). However, there are some exceptions. High dissolved zinc concentrations of 5–88 µg/L have been found in coastal waters near Port Pirie, South Australia, which is impacted by a zinc-lead smelter (Batley 1995; Chakraborty and Owens 2014; Vandeleur 2020). Three other coastal sites in South Australia had zinc concentrations of 17–33 µg/L, likely due to a combination of factors such as agricultural runoff, nearby factories, large amounts of sewage effluent and stormwater runoff from heavily urbanised land (Chakraborty and Owens 2014). In the Derwent estuary in Tasmania, an average zinc concentration of 59 µg/L was recorded in New Town Bay, which is also impacted by zinc smelter effluent (Nyrstar Hobart 2022). In five NSW shipping ports, mean and maximum dissolved zinc concentrations ranged from 7.5–18 and 20–38 µg/L, respectively (Jahan and Strezov 2017), attributed to shipping activities.

Based on Australian STPs, typical concentrations for domestic/industrial wastewater influent are up to 120 µg Zn/L (NPI 2011). Based on international jurisdictions, up to 75% of zinc entering STPs is removed from wastewater by adsorption to sewage sludge, which may be applied to agricultural land as a biosolid (European Commission 2010; ICON 2001). Such removal of zinc in Australian STPs would result in up to 30 µg Zn/L discharged to surface water in effluent streams. However, a study monitoring wastewater effluent in Darwin Harbour found dissolved zinc concentrations ranging from 0.94–8.24 µg Zn/L in filtered outfall, with mean values of 1.69–4.11 µg Zn/L (French et al. 2015). As noted above, concentrations of zinc found in many Australian urban harbours have been low. Considering this, urban STP effluent discharge is not generally expected to result in zinc concentrations

exceeding default guideline values in Australian coastal waters, though it may contribute to these in some areas.

Some limited data is available on zinc concentrations in freshwaters impacted by human activity. One area where zinc levels are clearly elevated is in the Leichhardt River catchment around Mount Isa, Queensland, where dissolved zinc concentrations in surface waters at various sampling sites ranged from <5–293 µg/L (FRC Environmental 2022). Concentrations in numerous samples exceeded default guideline values (8 µg/L for *slightly to moderately disturbed* freshwater ecosystems at the 95% protection level) and concentrations from reference sites (maximum of 12 µg/L) (FRC Environmental 2022; Mackay and Taylor 2013). This area is impacted by a lead-zinc-silver mine. Dissolved zinc concentrations were highest during the wet and post-wet season, attributed to remobilisation of zinc from contaminated sediment, in which total zinc concentrations ranged between 58–1540 mg/kg. Dilute acid extraction, a method used to evaluate the bioavailable metal fraction, of the most recent samples gave zinc sediment concentrations of 185–246 mg/kg (FRC Environmental 2022). The highest of these concentrations exceed the default guideline value for sediments of 200 mg/kg dw.

A review of published data from 1977–1992 identified zinc concentrations in eastern Australian estuarine sediments ranging from 4–2400 mg/kg, with elevated concentrations attributed to local industry and port activities, stormwater runoff and STP discharge (Batley 1995). Several of these values significantly exceed the default guideline value for sediments of 200 mg/kg dw, the highest value of 2400 mg/kg being from the northern part of Lake Macquarie, New South Wales, which has been impacted by a lead/zinc smelter. A study undertaken over a decade later indicated that zinc concentrations in Lake Macquarie surface sediments had decreased, finding a mean concentration of 1003 mg/kg dw at a similar site close to the smelter (Roach 2005). This study noted that industrial metal loads had declined in the intervening years. Many other sediment studies have been published since the review, identifying elevated zinc concentrations in sediments around various urban and industrial centres. Areas with notably high reported concentrations include: Derwent River, Tasmania (up to 14,600 mg/kg dw, mean 2130 mg/kg dw); Sydney Harbour, New South Wales (up to 11,300 mg/kg dw, mean 518 mg/kg dw); Port Pirie, South Australia (up to 21,037 mg/kg, mean 3359 mg/kg) (Birch et al. 2020; Vandeleur 2020). Of these, both the Derwent River and Port Pirie have been impacted by zinc smelting.

Background concentrations of zinc in soils around Australia are variable and deriving 'normal' concentrations is difficult (Reimann and de Caritat 2017). The NEPM predicts ambient background concentrations for zinc ranging from 3–60 mg/kg in soils with an iron content range of 0.1–20% and no history of contamination (NEPC 2013). However, a study of data from a national geochemical survey, in which most sites were located far from human activity centres, presents measured soil concentrations of < 0.1–330 mg Zn/kg (Reimann and de Caritat 2017). In urbanised areas, a study of garden soils around Australia found concentrations of < 1–29,400 mg Zn/kg (Taylor et al. 2021). In the Sydney estuary catchment area, concentrations of 4–1807 mg Zn/kg were measured, and mean concentrations were highest in roadside soils at 490 mg Zn/kg, attributed to vehicular traffic and deterioration of zinc-containing car parts (Birch et al. 2011). While it is difficult to judge whether the urban zinc concentrations exceed NEPM EILs without locally derived ambient background concentrations and pH and CEC values for the soils, zinc concentrations in Australian soils are clearly elevated in urban areas due to human activity.

Environmental effects

The environmental effects of the zinc salts in this group will primarily result from the release of ionic zinc(2+) species into the environment. Although all living organisms require a trace levels of zinc for essential functions, zinc in excess can overwhelm homeostasis and can result in adverse effects (Hogstrand 2011).

Effects on Aquatic Life

Although zinc is an essential trace element, excessive zinc can have adverse effects on aquatic organisms. In fish and invertebrates, excess zinc can disrupt calcium homeostasis and cause inflammation of the gills (Hogstrand 2011; Muysen et al. 2006) and disrupt photosynthesis in algae (Kaur and Garg 2021; Phetchuay et al. 2019; Soto et al. 2011).

While sensitivity of aquatic organisms varies between taxa, zinc toxicity is predominantly caused by free Zn(2+) ions. Therefore, zinc toxicity will be highest when environmental conditions favour free Zn(2+) ion speciation. The most important toxicity modifying factors for zinc in aquatic environments are water hardness, pH and dissolved organic carbon (DCCEEW 2021b). Maximum zinc toxicity in freshwater is expected in waters with low hardness, circumneutral pH, and low dissolved organic carbon concentrations.

Acute and chronic ecotoxicity data for fish and invertebrates were obtained from data collated by DeForest et al. (2023). Data for algae were obtained from Price et al. (2022). References for individual ecotoxicity data are provided in the tables.

Acute toxicity

The following acute median lethal concentrations (LC50) and median effective concentrations (EC50) for model organisms across three trophic levels are presented in terms of dissolved zinc together with relevant water chemistry parameters: water hardness, pH, and dissolved organic carbon (DOC) concentration (milligrams of carbon per litre, mg C/L). Water hardness is the sum of Ca(2+) and Mg(2+) ions but is expressed in units of milligrams of calcium carbonate per litre (mg CaCO₃/L):

Taxon	Endpoint	Conditions
Fish (<i>Oncorhynchus mykiss</i>)	96h LC50 = 21 µg Zn/L Mortality	Hardness = 7 mg CaCO ₃ /L pH = 6.2 DOC = 0.6 mg C/L (Mebane et al. 2012)
Invertebrate (<i>Ceriodaphnia dubia</i>)	48h LC50 = 34 µg Zn/L Mortality	Hardness = 44 mg CaCO ₃ /L pH = 8.6 DOC = < 1 mg C/L (Vera et al. 2014)
Algae (<i>Chlorella sp.</i>)	72h EC50 = 17 µg Zn/L Growth inhibition	Hardness = 5 mg CaCO ₃ /L pH = 7.6 DOC = < 1 mg C/L (Price et al. 2022)

Chronic toxicity

The following chronic effective concentrations (EC10) for model organisms across three trophic levels are presented in terms of dissolved zinc together with relevant water chemistry parameters: water hardness, pH, and DOC concentration:

Taxon	Endpoint	Method
Fish (<i>Oncorhynchus mykiss</i>)	30d LC10 = 34.5 µg Zn/L Mortality	Hardness = 29 mg CaCO ₃ /L pH = 7.6 DOC = 0.3 mg C/L (De Schamphelaere and Janssen 2004)
Invertebrate (<i>Ceriodaphnia dubia</i>)	7d EC10 = 14 µg Zn/L Reproduction	Hardness = 46 mg CaCO ₃ /L pH = 7.8 DOC = 4.5 mg C/L (Nys et al. 2017)
Algae (<i>Chlorella sp.</i>)	72h EC10 = 1.8 µg Zn/L Growth inhibition	Hardness = 5 mg CaCO ₃ /L pH = 7.6 DOC = <1 mg C/L (Price et al. 2022)

While aquatic zinc toxicity is typically greatest at low hardness, circumneutral pH and low DOC concentrations, this is not always the case. For example, zinc toxicity to the Australian microalga *Chlorella sp.* significantly increased with increasing DOC concentration when the DOC used in the experiment was sampled from an Australian freshwater ecosystem (Price et al. 2023). This demonstrates that typical relationships between physico-chemical parameters

and toxicity can be altered by the specific water chemistry of a particular site, emphasising the importance of site-specific risk assessment.

The toxicity of dietary zinc to fish is much lower and more dependent on species and food type than in the case of waterborne zinc exposure, in which there is a clear positive relationship between toxicity and zinc concentration (Clearwater et al. 2002). For invertebrates, dietary exposure to zinc has been observed to have little effect on growth but significantly reduces reproduction in *Daphnia magna* (De Schamphelaere et al. 2004).

Effects on Sediment-Dwelling Life

The bioavailability and toxicity of Zn(2+) in sediments is strongly influenced by the physicochemical characteristics of the sediment, with bioavailability depending on sorption to particles and organic matter, binding to sulfides, and iron and manganese oxide solid phases, and whether the sediment is oxic or anoxic (Simpson et al. 2013).

Toxicity of Zn(2+) ions in sediments is typically highest in coarse, sandy sediments that have low organic carbon and sulfide content, and low iron and manganese oxyhydroxide concentrations (Burton Jr. et al. 2005; Simpson et al. 2013). In a study that assessed the toxicity of zinc-spiked sediment to eight Australian and New Zealand benthic invertebrates, all species were relatively tolerant to zinc (King et al. 2006b). Sensitivities ranged between LC50 710 to >4,500 µg Zn/L and LC50 >500–1,130 µg Zn/L for adult and juvenile amphipods, respectively (King et al. 2006b). The three most sensitive species all belonged to the *Melita* genus, which are epibenthic deposit feeders that are likely to be exposed to zinc via waterborne exposure and ingesting contaminated particulates (King et al. 2006a; King et al. 2006b).

Effects on Terrestrial Life

Zinc is an essential element for plant life as a metallic co-factor in over 300 enzymes and proteins (Gupta et al. 2016). Many crop plants require zinc concentrations in leaves to be >15–30 mg/kg dw for maximum yield, but growth inhibition occurs for concentrations of >100–700 mg/kg dw (Gupta et al. 2016). The availability of zinc to plant roots in soil depends on soil characteristics, activity of plant roots and microflora in rhizosphere. Typically, >90% of total soil zinc is present in an insoluble form. The major determining factor affecting zinc speciation in soil is pH; increased pH promotes adsorption of Zn(2+) to cation exchange sites of soil constituents, e.g. metal oxides and clay minerals (Gupta et al. 2016).

Toxicity studies performed on terrestrial invertebrates determined pH, cation exchange capacity, and clay and soil organic matter content to be the most important soil characteristics controlling zinc toxicity (Lock and Janssen 2001). Zinc LC50 values across six species ranged between 147–5150 mg/kg dw, with the greatest zinc toxicity observed at low pH, low clay content, and low organic matter (Lock and Janssen 2001). A large proportion of NOEC and EC10 values collated in Lock and Janssen (2001) across multiple invertebrate species and soil conditions were around or lower than 200 mg/kg. Soil-specific added contaminant limits for zinc are outlined by the National Environment Protection Council (NEPC 2013). The added contaminant limits that protect 80% of species, based on NOEC and EC10 values, are between 20–330 mg Zn/kg in soils with a pH between 4.0 to 7.5 and a cation exchange capacity of 5 to 60 centimole charge/kg (cmolc/kg).

References

- ANZECC & ARMCANZ (Australia and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand) (2000a) [Australian and New Zealand Guidelines for Fresh and Marine Water Quality \(Vol II\) Aquatic Ecosystems — Rationale and Background Information \(Chapter 8\)](#), ANZECC & ARMCANZ, accessed 19 April 2021.
- ANZECC & ARMCANZ (Australia and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand) (2000b) [Australian and New Zealand Guidelines for Fresh and Marine Water Quality \(Vol I\). The Guidelines \(Chapters 1-7\)](#), ANZECC & ARMCANZ, accessed 19 April 2021.
- ASEAN (Association of Southeast Asian Nations) (2019) [Annexes of the ASEAN Cosmetic Directive](#), ASEAN, accessed 16 May 2022.
- Ashworth DJ and Alloway BJ (2004) 'Soil mobility of sewage sludge-derived dissolved organic matter, copper, nickel and zinc', *Environmental Pollution*, **127**(1), pp 137-144, doi:doi.org/10.1016/S0269-7491(03)00237-9.
- ATSDR (Agency for Toxic Substances and Disease Registry) (2005) [Toxicological Profile for Zinc](#), U.S. Department of Health and Human Services, accessed 21 December 2022.
- Batley G (1995) Heavy metals and tributyltin in Australian coastal and estuarine waters. In: Zann LP and Sutton DC, ed. *State of the Marine Environment Report for Australia, Technical Annex 2, Pollution*, Department of the Environment, Sport and Territories, Australia, pp 63-72.
- Birch GF, Vanderhayden M and Olmos M (2011) 'The nature and distribution of metals in soils of the Sydney estuary catchment, Australia', *Water, Air, & Soil Pollution*, **216**, pp 581-604, doi:doi.org/10.1007/s11270-010-0555-1.
- Birch GF, Lee JH, Tanner E, Fortune J, Munksgaard N, Whitehead J, Coughanowr C, Agius J, Chrispijn J, Taylor U, Wells F, Bellas J, Besada V, Viñas L, Soares-Gomes A, Cordeiro RC, Machado W, Santelli RE, Vaughan M, Cameron M, Brooks P, Crowe T, Ponti M, Airoidi L, Guerra R, Puente A, Gómez AG, Zhou GJ, Leung KMY and Steinberg P (2020) 'Sediment metal enrichment and ecological risk assessment of ten ports and estuaries in the World Harbours Project', *Marine Pollution Bulletin*, **155**, pp 111129, doi:doi.org/10.1016/j.marpolbul.2020.111129.
- Bruland KW (1989) 'Complexation of zinc by natural organic ligands in the central North Pacific', *Limnology and Oceanography*, **34**(2), pp 269-285, doi:doi.org/10.4319/lm.1989.34.2.0269.
- Burton Jr. GA, Nguyen LTH, Janssen C, Baudo R, McWilliam R, Bossuyt B, Beltrami M and Green A (2005) 'Field validation of sediment zinc toxicity', *Environmental Toxicology and Chemistry*, **24**(3), pp 541-553, doi:doi.org/10.1897/04-031R.1.
- Chakraborty S and Owens G (2014) 'Metal distributions in seawater, sediment and marine benthic macroalgae from the South Australian coastline', *Int. J. Environ. Sci. Technol.*, **11**, pp 1259 - 1270, doi:doi.org/10.1007/s13762-013-0310-4.

Clearwater SJ, Farag AM and Meyer JS (2002) 'Bioavailability and toxicity of dietborne copper and zinc to fish', *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, **132**(3), pp 269-313, doi:doi.org/10.1016/S1532-0456(02)00078-9.

Cleven RFMJ, Janus JA, Annema JA and Slooff W (1993) [Integrated criteria document Zinc](#), Bilthoven, Netherlands, accessed 10 March 2022.

Commonwealth of Australia (2020) [Agricultural and Veterinary Chemicals Act 1994](#), Canberra, Australia, accessed 21 January 2023.

DCCEEW (Department of Climate Change, Energy, the Environment and Water) (2018a) [Australian and New Zealand Guidelines for Fresh and Marine Water Quality](#), Water Quality Australia website, accessed 21 January 2022.

DCCEEW (Department of Climate Change, Energy, the Environment and Water) (2018b) [Toxicant default guideline values for sediment quality](#), Water Quality Australia website, accessed 21 January 2022.

DCCEEW (Department of Climate Change, Energy, the Environment and Water) (2021a) [Toxicant default guideline values for aquatic ecosystem protection: Zinc in marine water](#), Water Quality Australia website, accessed 21 January 2023.

DCCEEW (Department of Climate Change, Energy, the Environment and Water) (2021b) [Toxicant default guideline values for aquatic ecosystem protection: Zinc in freshwater](#), Water Quality Australia website, accessed 21 May 2022.

De Schamphelaere KAC, Canli M, Van Lierde V, Forrez I, Vanhaecke F and Janssen CR (2004) 'Reproductive toxicity of dietary zinc to *Daphnia magna*', *Aquatic Toxicology*, **70**(3), pp 233-244, doi:doi.org/10.1016/j.aquatox.2004.09.008.

De Schamphelaere KAC and Janssen CR (2004) 'Bioavailability and Chronic Toxicity of Zinc to Juvenile Rainbow Trout (*Oncorhynchus mykiss*): Comparison with Other Fish Species and Development of a Biotic Ligand Model', *Environmental Science & Technology*, **38**(23), pp 6201-6209, doi:doi.org/10.1021/es049720m.

DeForest DK, Ryan AC, Tear LM and Brix KV (2023) 'Comparison of Multiple Linear Regression and Biotic Ligand Models for Predicting Acute and Chronic Zinc Toxicity to Freshwater Organisms', *Environmental Toxicology and Chemistry*, doi:doi.org/10.1002/etc.5529.

Eisler R (U.S. Department of the Interior) (1993) [Zinc Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review](#), accessed 21 May 2022.

EU (European Union) (2009) [Regulation \(EC\) No 1223/2009 of the European Parliament and of the Council](#), accessed 21 May 2022.

European Commission (2010) [European Union Risk Assessment Report - Zinc Metal](#), Joint Research Centre-Institute for Health and Human Protection, accessed 16 December 2022.

FRC Environmental (2022) *Mount Isa Mines 2021 – 2022 Receiving Environment Monitoring Program*

French VA, Codi King S, Kumar A, Northcott G, McGuinness K and Parry D (2015) 'Characterisation of microcontaminants in Darwin Harbour, a tropical estuary of northern Australia undergoing rapid development', *Science of The Total Environment*, **536**, pp 639-647, doi:doi.org/10.1016/j.scitotenv.2015.07.114.

Galvanizers Association of Australia (n.d.) [Three ways galvanizing protects steel](#), accessed 15 February 2023.

Goodwin FE (2017) Zinc Compounds. In: ed. *Kirk-Othmer Encyclopedia of Chemical Technology*, John Wiley & Sons, Inc.

Government of Canada (2022) [Zinc facts](#), accessed 15 May 2022.

Gray SR and Becker NSC (2002) 'Contaminant flows in urban residential water systems', *Urban Water*, **4**(4), pp 331-346, doi:doi.org/10.1016/S1462-0758(02)00033-X.

Gupta N, Ram H and Kumar B (2016) 'Mechanism of Zinc absorption in plants: uptake, transport, translocation and accumulation', *Reviews in Environmental Science and Bio/Technology*, **15**(1), pp 89-109, doi:doi.org/10.1007/s11157-016-9390-1.

Haynes D and Johnson JE (2000) 'Organochlorine, heavy metal and polyaromatic hydrocarbon pollutant concentrations in the Great Barrier Reef (Australia) environment: a review', *Marine Pollution Bulletin*, **41**(7), pp 267-278, doi:doi.org/10.1016/S0025-326X(00)00134-X.

Hogstrand C (2011) 3 - Zinc. In: Wood CM, Farrell AP and Brauner CJ, ed. *Fish Physiology*, Academic Press, pp 135-200.

Huang CP, Elliott HA and Ashmead RM (1977) 'Interfacial Reactions and the Fate of Heavy Metals in Soil-Water Systems', *Water Pollution Control Federation*, **49**(5), pp 745-756.

ICON (European Commission) (2001) [Pollutants in urban waste water and sewage sludge](#), accessed 9 June 2022.

International Zinc Association (2023) [Zinc Environmental Profile: Life Cycle Assessment - 2023 Update Based on 2021 Industry Data](#), accessed November 2023.

Jahan S and Strezov V (2017) 'Water quality assessment of Australian ports using water quality evaluation indices', *PLOS ONE*, **12**(12), pp e0189284, doi:doi.org/10.1371/journal.pone.0189284.

Kaur H and Garg N (2021) 'Zinc toxicity in plants: a review', *Planta*, **253**(6), pp 129, doi:doi.org/10.1007/s00425-021-03642-z.

King C, Gale S and Stauber J (2006a) 'Acute toxicity and bioaccumulation of aqueous and sediment-bound metals in the estuarine amphipod *Melita plumulosa*', *Environmental Toxicology: An International Journal*, **21**(5), pp 489-504, doi:doi.org/10.1002/tox.20211.

King CK, Gale SA, Hyne RV, Stauber JL, Simpson SL and Hickey CW (2006b) 'Sensitivities of Australian and New Zealand amphipods to copper and zinc in waters and metal-spiked sediments', *Chemosphere*, **63**(9), pp 1466-1476, doi:doi.org/10.1016/j.chemosphere.2005.09.020.

- Lock K and Janssen CR (2001) 'Modeling zinc toxicity for terrestrial invertebrates', *Environmental Toxicology and Chemistry*, **20**(9), pp 1901-1908, doi:doi.org/10.1002/etc.5620200907.
- Long ER, Macdonald DD, Smith SL and Calder FD (1995) 'Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments', *Environmental Management*, **19**(1), pp 81-97, doi:doi.org/10.1007/BF02472006.
- Mackay AK and Taylor MP (2013) 'Floodwater Metal Contaminants in an Australian Dryland River: A Baseline for Assessing Change Downstream of a Major Lead-Zinc-Silver and Copper Mine', *Journal of Environmental Quality*, **42**(2), pp 474-483, doi:doi.org/10.2134/jeq2010.0349.
- Mantoura RFC, Dickson A and Riley JP (1978) 'The complexation of metals with humic materials in natural waters', *Estuarine and Coastal Marine Science*, **6**(4), pp 387-408, doi:doi.org/10.1016/0302-3524(78)90130-5.
- McGeer JC, Brix KV, Skeaff JM, DeForest DK, Brigham SI, Adams WJ and Green A (2003) 'Inverse relationship between bioconcentration factor and exposure concentration for metals: Implications for hazard assessment of metals in the aquatic environment', *Environmental Toxicology and Chemistry*, **22**(5), pp 1017-1037, doi:doi.org/10.1002/etc.5620220509.
- Mebane CA, Dillon FS and Hennessy DP (2012) 'Acute toxicity of cadmium, lead, zinc, and their mixtures to stream-resident fish and invertebrates', *Environmental Toxicology and Chemistry*, **31**(6), pp 1334-1348, doi:doi.org/10.1002/etc.1820.
- Mertens J and Smolders E (2013) Zinc. In: Alloway BJ, ed. *Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability*, Springer Netherlands, Dordrecht, pp 465-493.
- Meylan S, Behra R and Sigg L (2004) 'Influence of Metal Speciation in Natural Freshwater on Bioaccumulation of Copper and Zinc in Periphyton: A Microcosm Study', *Environmental Science & Technology*, **38**(11), pp 3104-3111, doi:doi.org/10.1021/es034993n.
- Muysen BTA, De Schampelaere KAC and Janssen CR (2006) 'Mechanisms of chronic waterborne Zn toxicity in *Daphnia magna*', *Aquatic Toxicology*, **77**(4), pp 393-401, doi:doi.org/10.1016/j.aquatox.2006.01.006.
- NEPC (2013) [National Environment Protection \(Assessment of Site Contamination\) Measure 1999](#), Canberra, Australia, accessed 15 April 2021.
- NICNAS (2006) [Australian High Volume Industrial Chemical List](#), National Industrial Chemicals Notification and Assessment Scheme (NICNAS), accessed 23 January 2023.
- NICNAS (2014a) [Zinc chloride \(ZnCl₂\): Human health tier II assessment](#), National Industrial Chemicals Notification and Assessment Scheme (NICNAS), accessed 20 January 2023.
- NICNAS (2014b) [Nitric acid, zinc salt: Human health tier II assessment](#), National Industrial Chemicals Notification and Assessment Scheme (NICNAS), accessed 20 January 2023.
- NICNAS (2014c) [Soluble zinc salts: Human health tier II assessment](#), National Industrial Chemicals Notification and Assessment Scheme (NICNAS), accessed 2 September 2022.

NICNAS (2017) [Zinc Borates: Human health tier II assessment](#), National Industrial Chemicals Notification and Assessment Scheme (NICNAS), accessed 20 January 2023.

NPI (National Pollutant Inventory) (2011) [Emission Estimation Technique Manual for Sewage and Wastewater Treatment](#), accessed 10 June 2022.

NPI (n.d.-a) [2021/2022 data within Australia - Zinc & compounds from All Sources](#), National Pollutant Inventory (NPI), accessed October 2023.

NPI (National Pollutant Inventory) (n.d.-b) [Zinc and compounds](#), accessed 10 March 2022.

NPI (National Pollutant Inventory) (n.d.-c) [Substance list and thresholds](#), accessed February 2023.

NRMMC (2004) [National Water Quality Management Strategy, Guidelines for Sewerage Systems Biosolids Management](#), NRMMC, accessed 29 April 2021.

Nyrstar Hobart (2022) [Triennial Public Environment Report 2019 – 2021](#), accessed 22 February 2024.

Nys C, Janssen CR and De Schampelaere KAC (2017) 'The effect of pH on chronic zinc toxicity differs between daphnid species: Development of a preliminary chronic zinc *Ceriodaphnia dubia* bioavailability model', *Environmental Toxicology and Chemistry*, **36**(10), pp 2750-2755, doi:doi.org/10.1002/etc.3831.

NZ EPA (New Zealand Environment Protection Agency) (2019) [Cosmetic Products Group Standard 2006](#), accessed 3 May 2022.

Paz-Villarraga CA, Castro ÍB and Fillmann G (2022) 'Biocides in antifouling paint formulations currently registered for use', *Environmental Science and Pollution Research*, pp 1-12, doi:doi.org/10.1007/s11356-021-17662-5.

Phetchuay P, Peerakietkhajorn S, Duangpan S and Buapet P (2019) 'Toxicity effects of copper and zinc on the photosynthetic efficiency and oxidative stress-related parameters of the green alga *Chlorella vulgaris* Beijerinck', *Journal of Fisheries and Environment*, **43**(2), pp 14-26, doi:doi.org/10.5555/20203155095.

Price GAV, Stauber JL, Holland A, Koppel DJ, Van Genderen EJ, Ryan AC and Jolley DF (2022) 'The influence of hardness at varying pH on zinc toxicity and lability to a freshwater microalga, *Chlorella* sp', *Environmental Science: Processes & Impacts*, doi:doi.org/10.1039/D2EM00063F.

Price GAV, Stauber JL, Jolley DF, Koppel DJ, Van Genderen EJ, Ryan AC and Holland A (2023) 'Natural organic matter source, concentration, and pH influences the toxicity of zinc to a freshwater microalga', *Environmental Pollution*, **318**, pp 120797, doi:doi.org/10.1016/j.envpol.2022.120797.

Qu R, Feng M, Wang X, Qin L, Wang C, Wang Z and Wang L (2014) 'Metal accumulation and oxidative stress biomarkers in liver of freshwater fish *Carassius auratus* following in vivo exposure to waterborne zinc under different pH values', *Aquatic Toxicology*, **150**, pp 9-16, doi:doi.org/10.1016/j.aquatox.2014.02.008.

Reimann C and de Caritat P (2017) 'Establishing geochemical background variation and threshold values for 59 elements in Australian surface soil', *Science of the Total Environment*, **578**, pp 633-648, doi:doi.org/10.1016/j.scitotenv.2016.11.010.

Roach AC (2005) 'Assessment of metals in sediments from Lake Macquarie, New South Wales, Australia, using normalisation models and sediment quality guidelines', *Marine Environmental Research*, **59**(5), pp 453-472, doi:doi.org/10.1016/j.marenvres.2004.07.002.

Simpson SL, Batley GE and Chariton AA (2013) *Revision of the ANZECC/ARMCANZ Sediment Quality Guidelines*, CSIRO Land and Water, accessed 16 January 2023 doi.org/10.4225/08/5894c6184320c.

Soto P, Gaete H and Hidalgo ME (2011) 'Assessment of catalase activity, lipid peroxidation, chlorophyll-a, and growth rate in the freshwater green algae *Pseudokirchneriella subcapitata* exposed to copper and zinc', *Latin American Journal of Aquatic Research*, **39**(2), pp 280-285, doi:doi.org/10.3856/vol39-issue2-fulltext-9.

Stephan CH, Courchesne F, Hendershot WH, McGrath SP, Chaudri AM, Sappin-Didier V and Sauvé S (2008) 'Speciation of zinc in contaminated soils', *Environmental Pollution*, **155**(2), pp 208-216, doi:doi.org/10.1016/j.envpol.2007.12.006.

Taylor MP, Isley CF, Fry KL, Liu X, Gillings MM, Rouillon M, Soltani NS, Gore DB and Filippelli GM (2021) 'A citizen science approach to identifying trace metal contamination risks in urban gardens', *Environment International*, **155**, pp 106582, doi:doi.org/10.1016/j.envint.2021.106582.

Tjandraatmadja G and Diaper C (CSIRO) (2006) [Sources of critical contaminants in domestic wastewater](#), CSIRO, accessed 17 June 2022.

Uc-Peraza RG, Castro ÍB and Fillmann G (2022) 'An absurd scenario in 2021: Banned TBT-based antifouling products still available on the market', *Science of The Total Environment*, **805**, pp 150377, doi:doi.org/10.1016/j.scitotenv.2021.150377.

Vallee BL and Falchuk KH (1993) 'The biochemical basis of zinc physiology', *Physiological Reviews*, **73**(1), pp 79-118, doi:doi.org/10.1152/physrev.1993.73.1.79.

Vandeleur H (2020) *Port Pirie Phase 1 Project: Measuring, modelling and managing legacies of marine pollution as new resources*, accessed 10 March 2022 doi.org/10.13140/RG.2.2.21127.88485.

Vera CL, Hyne RV, Patra R, Ramasamy S, Pablo F, Julli M and Kefford BJ (2014) 'Bicarbonate toxicity to *Ceriodaphnia dubia* and the freshwater shrimp *Paratya australiensis* and its influence on zinc toxicity', *Environmental Toxicology & Chemistry*, **33**(5), pp 1179-86, doi:doi.org/10.1002/etc.2545.

WHO (World Health Organization) (2001) [Environmental Health Criteria 221: Zinc](#), accessed 19 February 2023.

Zoumis T, Schmidt A, Grigorova L and Calmano W (2001) 'Contaminants in sediments: remobilisation and demobilisation', *Science of The Total Environment*, **266**(1), pp 195-202, doi:doi.org/10.1016/S0048-9697(00)00740-3.

SAFETY

