Environmental fate and effects of zinc ions

Evaluation statement

15 April 2024

Draft

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AICIS evaluation statement

Subject of the evaluation

Environmental fate and effects of zinc ions

Parameters of evaluation

This evaluation provides reference information on the environmental fate and effects of zinc ions, which may be released into the environment from the industrial uses of zinc-containing substances in Australia. It also includes a review of Australian environmental zinc monitoring and emission reporting and compares reported levels with national threshold guideline levels. This evaluation will inform future evaluations of zinc-containing substances that may dissolve or transform to release zinc ions under environmental conditions.

This evaluation does not assess the environmental risks of any specific chemical but provides reference information on environmental risks of zinc-containing chemicals.

Reason for the evaluation

Evaluation is needed to provide information on environmental risks.

Summary of evaluation

Summary of introduction, use and end use

Based on Australian and international use information, zinc-containing chemicals are expected to be used in a wide range of products. Major uses are likely to be in:

- metal products
- construction materials
- personal care products
- paint and coating products
- tyres and rubber
- fertilisers
- electronic products
- textile products.

The highest introduction volume is for zinc metal (CAS RN 7440-66-6). Reported information from Australia and international jurisdictions indicate that zinc metal is introduced into Australia in volumes of up to 1.4 million tonnes per year.

Environment

Summary of environmental hazard characteristics

Although zinc is an essential trace element for all living organisms, excessive environmental zinc concentrations are of concern as they can overwhelm homeostasis and result in adverse effects on aquatic and terrestrial life.

Summary of environmental risk

Environmental monitoring studies of Australian coastal waters, including urban harbours, have found zinc concentrations to be generally below national guideline values for the protection of aquatic ecosystems. However, zinc concentrations in surface waters and sediments exceed guideline values in areas impacted by zinc smelting, urban stormwater runoff, shipping activities and sewage treatment plant (STP) effluent. Zinc emissions from these sources may result from introduction of industrial chemicals, such as manufacture of zinc metal, and industrial uses of zinc-containing substances such as in galvanised objects, rubber, fertilisers and personal care products.

Significantly elevated zinc concentrations are present in soils impacted by urban pollution. High concentrations in roadside soils are likely due to deterioration of zinc-containing materials in vehicles, such as galvanised steel and tyre rubber.

Conclusions

This evaluation provides information on the environmental fate and effects of zinc ions, which may be released into the environment from the industrial uses of zinc-containing substances in Australia.

Elevated levels of zinc above national guideline values have been detected in some areas in Australia. Industrial uses of chemicals that may contribute to these elevated levels include:

- manufacture of zinc metal
- galvanised objects
- rubber products
- fertilisers
- personal care products.

Based on the available information, the Executive Director proposes that zinc compounds for these industrial uses be considered through our Evaluation Selection Analysis method alongside with other potential candidates for evaluation. Any such initiated evaluations may identify specific risks and recommend means for managing those risks. Initiated evaluations would be notified through updates to AICIS' Evaluations Rolling Action Plan.

Supporting information

Rationale

The evaluation selection analysis (ESA) indicated that environmental zinc levels in Australia may be above nationally recognised levels of concern in many areas, and the introduction and use of zinc-containing industrial chemicals is likely to contribute.

Relevant physical and chemical properties

Zinc compounds are generally colourless unless the non-zinc components are coloured (Goodwin 2017). The water solubility of zinc compounds varies widely, with the most soluble being salts of strong inorganic acids, such as zinc sulfate and chloride, or short-chain carboxylic acids, such as zinc acetate. Dissolution of water soluble zinc salts results in dissociation of the corresponding anions and the zinc(2+) cation.

Introduction and use

Australia

There are approximately 390 zinc-containing chemicals listed on the Australian Inventory of Industrial Chemicals (the Inventory). Of these zinc-containing chemicals, three are listed on the 2006 Australian High Volume Industrial Chemicals List (AHVICL) with total introduction volumes above 1000 tonnes per year (t/year). These are zinc metal (CAS RN 7440-66-6) at 100,000–999,999 t/year and zinc sulfate (CAS RN 7733-02-0) and phosphorodithioic acid, O,O-bis(1,3-dimethylbutyl and isopropyl)esters, zinc salts (CAS RN 84605-29-8) at 1000–9,999 t/year (NICNAS 2006). Recent information on global zinc production indicates that Australia produced 1.4 million tonnes of zinc metal in 2020 (Government of Canada 2022), suggesting that introduction volumes of this chemical have increased since the 2006 AHVICL listing.

These chemicals have reported uses in absorbents and adsorbents, colouring agents, construction material additives, corrosion inhibitors, insulating agents, welding and soldering agents, flotation agents, lubricants, hydraulic fluids, mining and metal extraction and manufacture of chemicals, amongst others.

All other zinc-containing chemicals have either reported introduction volumes under 1000 t/year or no available Australian use, import or manufacturing information. In addition to the uses above, some reported uses of these other chemicals are in cleaning/washing agents, fixing agents, latex coagulants, catalysts, treating textiles, paper bleaching and flame retardants (NICNAS 2014a; NICNAS 2014b; NICNAS 2014c; NICNAS 2017).

International

Global production of zinc in 2020 equated to around 12 million tonnes, and Australia is a major producer at 1.4 million tonnes (11.6%) (Government of Canada 2022). Zinc and zinc compounds have a wide range of uses, particularly in galvanising, die casting and production of brass. Other major uses include in fertilisers, tyres and rubber, paints, ceramics, wood preservation, fluxes, batteries and rayon manufacture (Goodwin 2017).

In 2021, nearly 60% of zinc produced worldwide was used for galvanising to protect steel from corrosion, and around 30% used to produce alloys with aluminium (die casting) and copper (brass) (International Zinc Association 2023). The main reported applications of zinc products were in construction (45%), transport (25%), consumer goods and electrical appliances (23%) and general engineering (7%).

Existing Australian regulatory controls

Environment

In Australia, default guideline values for zinc in water and sediments are outlined in the Australia New Zealand Guidelines for Fresh and Marine Water Quality (ANZ Water Quality Guidelines) (DCCEEW 2018a). These values represent a starting point for assessing water quality and are recommended for generic applications in the absence of more relevant guideline values, such as site-specific guideline values that account for local conditions. Very high reliability default guideline values have been determined for zinc in aquatic environments (DCCEEW 2018a).

In freshwater, the default guideline value for protection of 95% of species is 8 µg Zn/L (for hardness of 30 mg $CaCO_3$/L), recommended for application to *slightly-moderately disturbed* ecosystems. (DCCEEW 2021b). This was derived from 85 chronic data points covering 20 species from 6 taxonomic groups.

In marine waters, the default guideline value for protection of 95% of species is 8.0 µg Zn/L (for hardness of 30 mg $CaCO_3$/L), recommended for *slightly-moderately disturbed* ecosystems (DCCEEW 2021a). This was derived from 20 chronic data points covering 16 species from 7 taxonomic groups.

The recommended default sediment quality guideline value for zinc is 200 mg/kg dry weight (dw) (DCCEEW 2018b). This value has been adapted from US estimates due to the lack of high-quality Australia/New Zealand data (DCCEEW 2018b; Long et al. 1995; Simpson et al. 2013).

In soils, added contaminant limits for zinc in the *National Environment Protection (Assessment of Site Contamination) Measure 1999* (NEPM) have been developed to protect soil-dwelling species (NEPC 2013). Ecological investigation limits (EILs) represent the level above which further investigation or evaluation is required and are the sum of the added contaminant limit and ambient background concentration at the site.

For soils where the contaminant has been present for less than 2 years (i.e. a freshly contaminated soil), the added contaminant limit for the protection of 80% of species, applied to urban residential areas and public open space, is 25–500 mg added Zn/kg, depending on soil pH and cation exchange capacity (CEC). For aged contamination in soils, in which toxic effects of zinc are expected to be lower, the corresponding added contaminant limit range is 70–1300 mg added Zn/kg (NEPC 2013).

For irrigated soil, a cumulative contaminant loading limit (CCL) guideline value has been set at 300 kg Zn/ha (ANZECC & ARMCANZ 2000b). Nationally, limits on zinc contamination in biosolids of 200–250 mg Zn/kg are recommended if state or territory guidelines are unavailable (NRMMC 2004).

Zinc and zinc compounds are subject to reporting under the Australian National Pollutant Inventory (NPI). Under the NPI, emissions of zinc and zinc compounds are required to be reported annually by facilities that exceed 10 tonnes (NPI n.d.-c).

International regulatory status

This section provides an overview of the international regulatory status of relevant classes of zinc compounds. The regulatory status of specific zinc-containing chemicals is not covered.

European Union

Water soluble zinc salts (unless listed elsewhere) are restricted to a maximum concentration of 1% zinc in cosmetic products under Annex III of EC No 1223/2009 (EU 2009).

New Zealand

Water soluble zinc salts are restricted to a maximum concentration of 1% zinc in cosmetic products under Schedule 5 of the Cosmetic Products Group Standard 2006 (NZ EPA 2019).

Asia

Water soluble zinc salts are restricted to a maximum concentration of 1% zinc in cosmetic products under Annex III of the ASEAN Cosmetic Directive (ASEAN 2019).

Environmental exposure

While zinc is a naturally occurring element, human activities are a large source of zinc emissions to the Australian environment. Available information indicates that zinc and zinc compounds are released to all environmental compartments as a result of introduction and use of zinc-containing industrial chemicals.

In Australia, the National Pollutant Inventory (NPI) states that major industry sources of zinc emissions to air, water and soil are from processing of zinc (especially mining and refining), galvanising plants, sewage treatment plants (STPs) and waste sites. Diffuse sources of zinc emissions to soil and water are largely attributed to corrosion of galvanised structures, followed by uncontrolled release from use of fertilisers and herbicides (NPI n.d.-b). Zinc used in tyre rubber may also be released to soils around roads due to tyre road wear and be washed into aqueous environments via stormwater (DCCEEW 2021a).

In 2021–2022, approximately 1700 tonnes of zinc and zinc compounds were estimated to have been released into the Australian environment from all reporting sources:

- 76% of emissions were reported to be to air
- 14% to water
- 11% to land.

The highest emitting industries were metal ore mining, metal manufacture and waste treatment (NPI n.d.-a).

Galvanising involves applying zinc coating to steel or iron to prevent corrosion. The zinc coating provides a physical barrier and develops a protective patina made up of insoluble

zinc oxides, hydroxides and carbonates, and basic zinc salts depending on the environment. It also acts as a sacrificial anode, corroding preferentially to the underlying steel (Galvanizers Association of Australia n.d.). Sacrificial zinc anodes slowly release zinc to the aquatic and terrestrial environments in which they are used (Paz-Villarraga et al. 2022; WHO 2001).

Another source of zinc contamination in marine ports is zinc-based antifouling paints used on ship hulls. Use of zinc-based antifoulants has become particularly common following a widespread ban on the use of tributyltin for this purpose in 2008 (Uc-Peraza et al. 2022). Important zinc-based antifoulants include the Inventory listed chemical zinc pyrithione (CAS RN 13463-41-7) and zineb (CAS RN 12122-67-7, not listed on the Inventory), which are typically formulated to concentrations of around 4–6% (w/w) in antifouling paints (Paz-Villarraga et al. 2022). Antifouling paints are regulated under the *Agricultural and Veterinary Chemicals Act 1994* (Commonwealth of Australia 2020). Zinc-based antifoulants are therefore not considered industrial uses under the *Industrial Chemicals Act 2019* and are beyond the parameters of AICIS evaluations.

Zinc compounds are also released to surface waters via effluent from sewage treatment plants. An Australian study found zinc concentrations in bathroom wastewater up to 6.3 mg/L (Tjandraatmadja and Diaper 2006). Around 73% of household zinc emissions to wastewater are reportedly from the bathroom and likely contributed to by personal care products such as sunscreen, deodorant and shampoo (Gray and Becker 2002; Tjandraatmadja and Diaper 2006).

Environmental fate

Dissolution, speciation, and partitioning

The use and introduction of industrial zinc-containing chemicals may release zinc compounds to the atmosphere, surface waters and soils, and ultimately form the zinc(2+) cation. The behaviour of the zinc(2+) ion depends on the chemistry of the environmental compartment into which it is released. Dissolved zinc will exist in natural waters as the free (hydrated) zinc(2+) ion, inorganic compounds and complexes, and complexes with dissolved organic matter (DOM), depending on the pH, water hardness, salinity and presence of DOM. Most of this zinc will partition to sediments via adsorption and precipitation but may be dissolved or desorbed due to decreasing pH, increasing salinity or oxidising conditions. Zinc in soils is expected to be strongly sorbed to particulates, and therefore have low mobility, but may be released due to decreasing pH or oxygen concentrations.

In the atmosphere, zinc is mainly bound to aerosols in an oxidised form. Zinc then partitions to soil and water via wet and dry deposition (ATSDR 2005).

In freshwaters, dissolved zinc speciates into the hydrated zinc(2+) ion and zinc carbonates, hydroxide and sulfate (Eisler 1993). The hydrated zinc(2+) ion is most prominent at low pH, low alkalinity and low water hardness (DCCEEW 2021b; Eisler 1993). Zinc carbonate and hydroxide are more prevalent at higher pH, alkalinity and hardness (Eisler 1993; Qu et al. 2014). Zinc also forms complexes with DOM, which is favoured under alkaline conditions (DCCEEW 2021b; Meylan et al. 2004).

In marine water zinc exists in a dissolved state, as a solid precipitate, or adsorbed to particle surfaces. Dissolved zinc is present as the hydrated zinc(2+) ion, inorganic complexes or complexes with DOM. Zinc speciation depends on pH, salinity and the presence of DOM. At neutral pH, such as in estuarine waters, the free (hydrated) zinc(2+) ion is the major species, while zinc hydroxides are predominant at pH > 8 (DCCEEW 2021b; Eisler 1993). Zinc sulfate and chloro-complexes also form, becoming more significant at higher salinity (Eisler

1993; Mantoura et al. 1978). In the presence of DOM, most dissolved zinc is present as Zn-DOM complexes (Bruland 1989; Eisler 1993).

Most dissolved zinc in natural waters will partition to sediments. Zinc in aquatic environments is adsorbed onto iron and manganese oxides, clay minerals, or organic materials (Eisler 1993). Dissolved zinc also precipitates as zinc hydroxide, sulfide, carbonate, insoluble organic complexes and with iron and manganese oxyhydroxides (ATSDR 2005; Eisler 1993). The extent of zinc sorption depends on pH and salinity. Zinc will sorb more readily at pH > 7 and low salinity. Inorganic zinc compounds also precipitate more readily at higher pH (ATSDR 2005). Zinc species may be dissolved or desorbed from sediments as pH decreases or salinity increases (ATSDR 2005) and under anoxic conditions (DCCEEW 2021a). Zinc may also be remobilised when sediments are oxidised due to disturbance by organisms or during flooding events (Zoumis et al. 2001).

In soils, zinc sorbs to organic matter, oxyhydroxides and sometimes to clay minerals (Huang et al. 1977; Mertens and Smolders 2013). Dissolved zinc may also precipitate as a sulfide, carbonate, (hydr)oxides or calcium zincate, depending on the chemical species present in soil (ATSDR 2005). Zinc solubility, and therefore mobility, is largely controlled by sorption processes. Zinc sorbs strongly to soil particulates but is desorbed as pH decreases (ATSDR 2005; Mertens and Smolders 2013; Stephan et al. 2008). Zinc may also be released from (hydr)oxide phases via reductive dissolution when oxygen concentrations decrease, such as during flooding events. However, under persistent low-oxygen conditions, the precipitation of poorly soluble zinc sulfide may limit zinc mobility (ATSDR 2005). In the soil solution, zinc is present as the free zinc(2+) ion and Zn-DOM complexes. (Stephan et al. 2008). However, formation of Zn-DOM complexes does not seem to prevent sorption of zinc to the solid phase, and overall zinc mobility in soils is expected to be low (Ashworth and Alloway 2004; ATSDR 2005).

Bioaccumulation

Zinc is essential to all organisms (ATSDR 2005; Vallee and Falchuk 1993; WHO 2001). The bioaccumulation of zinc is a complex area because of its essentiality. Some degree of accumulation is normal and does not necessarily signify contamination issues. Zinc does not generally biomagnify through food chains (ATSDR 2005; Cleven et al. 1993; McGeer et al. 2003).

For zinc, bioconcentration factors (BCFs) are not reliable indicators of adverse effects. When zinc concentrations are low, aquatic organisms will actively accumulate zinc to perform essential functions (McGeer et al. 2003). This natural concentration means that BCFs, as ratios of the concentration in biota to exposure concentration, cannot be considered to reflect toxicity (WHO 2001). When environmental concentrations exceed essential requirements, aquatic organisms can regulate their body zinc concentrations within certain limits, meaning that biota concentrations do not necessarily reflect exposure concentration (McGeer et al. 2003; WHO 2001). A review of published data showed zinc concentration to be well regulated across eight species groups when exposure concentrations were increased, and only slight increases in whole-body concentration were observed over a large range of exposure concentrations (McGeer et al. 2003). Data indicated inconsistent relationships between whole-body zinc concentration and increasing exposure level. Zinc BCF data showed an inverse relationship to exposure concentration.

Zinc has not been shown to bioaccumulate in plant life, with concentrations not exceeding those in soils (ATSDR 2005; Cleven et al. 1993). Zinc concentrations depend on the plant species and local soil composition, and accumulation tends to decrease with increasing pH.

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; Muyssen 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 $CaCO_3$/L):

Taxon	Endpoint	Conditions
Fish (*Oncorhynchus mykiss*)	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 (*Ceriodaphnia dubia*)	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 (*Chlorella sp.*)	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 (*Oncorhynchus mykiss*)	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 (*Ceriodaphnia dubia*)	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 (*Chlorella sp.*)	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).

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