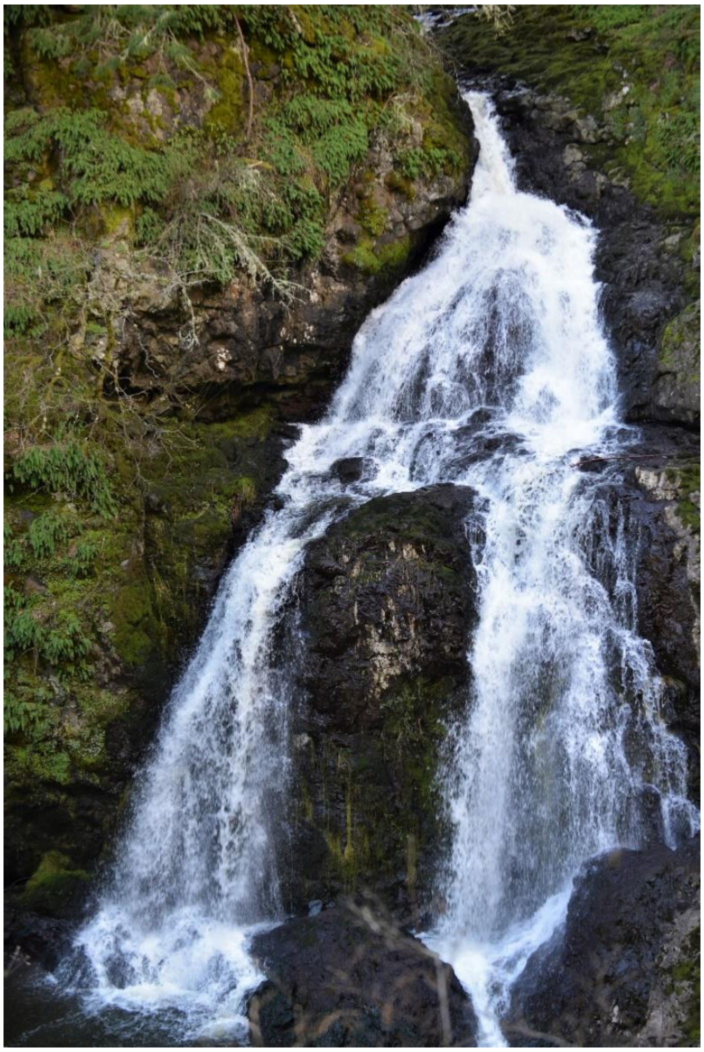
WATER QUALITY GUIDELINE SERIES

Zinc Water Quality Guidelines – Marine Aquatic Life, Livestock Watering, and Irrigation (Reformatted Guideline from 1997)

Ministry of Environment and Climate Change Strategy
Water Protection & Sustainability Branch



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BRITISH COLUMBIA

The Water Quality Guideline Series is a collection of British Columbia (B.C.) Ministry of Environment and Climate Change Strategy water quality guidelines. Water quality guidelines are developed to protect a variety of water values and uses: aquatic life, drinking water sources, recreation, livestock watering, irrigation, and wildlife. The Water Quality Guideline Series focuses on publishing water quality guideline technical reports and guideline summaries using the best available science to aid in the management of B.C.'s water resources. For additional information on B.C.'s approved water quality parameter specific guidelines, visit:

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Original Author:
Nagpal, Narender

Notes on Reformatted Version:
Sections of this report on freshwater aquatic life, industrial water use, drinking water and recreation have been removed and all remaining text are from the original 1997 document. Freshwater aquatic life, drinking water and recreation guidelines can be found in separate documents on the B.C. water quality guidelines website. B.C. no longer develops or supports guidelines for industrial water use.

Cover Photograph:
Location: Sitting Lady Falls, Vancouver Island, B.C.

SUMMARY

This document is one in a series that establishes ambient water quality guidelines, formerly known as criteria, for British Columbia (Table S1). This document is mainly based on a report prepared by the BC Ministry of Environment, Lands and Parks for the Canadian Council of Ministers of the Environment (CCME). It sets guidelines for zinc (Zn) to protect marine aquatic life and agricultural water (irrigation and livestock watering) uses.

Table S1. Recommended guidelines for zinc.

Water use	Chronic long-term (µg: Total Zn/L)	Acute short-term (µg: Total Zn/L)
Marine Life	10	55
Irrigation		
Soil pH < 6		1000
Soil pH 6 - < 7		2000
Soil pH ≥ 7		5000
Livestock Watering		2000

Zinc guidelines were not set for wildlife, since suitable data documenting the effects of zinc for these uses were not available in the literature.

Zinc is an essential element in trace amounts for plants and animals. In mammals, it plays a vital role in the biosynthesis of nucleic acids, RNA polymerases, and DNA polymerases and, thus, is involved in the healing processes of tissues in the body. Other physiological processes such as hormone metabolism, immune response, and stabilization of ribosome and membranes also require Zn.

Zinc poisoning in animals (e.g., from ingesting or exposure to galvanized metal objects, certain paints and fertilizers, zinc-containing coins, etc.) have been documented. Clinical manifestations of Zn deficiency in animals include growth retardation, testicular atrophy, skin changes, and poor appetite. Zinc is ubiquitous in the environment and its deficiency in animals may be considered an unlikely problem. Nevertheless, Zn deficiency and related problems in animals and plants have been reported in the literature.

The concentration of Zn in natural waters is generally low, but on occasion high levels have been measured in natural environments. High levels of zinc are always found in contaminated waters or waters flowing through a bedrock system containing Zn deposits.

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1. INTRODUCTION

Zinc (Zn) is an essential element in trace amounts for plants and animals. In mammals, it plays a vital role in the biosynthesis of nucleic acids, RNA polymerases, and DNA polymerases and, thus, is involved in the healing processes of tissues in the body. Other physiological processes, including hormone metabolisms, immune response, and stabilization of ribosome and membranes, require zinc (Moore and Ramamoorthy 1984). Clinical manifestations of zinc deficiency in animals include growth retardation, testicular atrophy, skin changes, and poor appetite (Prasad 1979). Zinc is ubiquitous in the environment and its deficiency in humans and animals may be considered an unlikely problem. Nevertheless, zinc deficiency and related problems in animals and plants have been reported in the literature (Eisler 1993). Zinc toxicosis is not a common problem, but Zn poisoning in animals (e.g., from ingesting or exposure to galvanize metal objects, certain paints and fertilizers, zinc-containing coins, etc.) have been documented (Eisler 1993).

Water quality guidelines are used by provincial, territorial, and federal agencies to assess water quality problems and manage competing uses of water. The Canadian Council of Ministers of the Environment recognized the increasing importance of water quality guidelines and asked its task force on Water Quality Guidelines to prepare water quality guidelines relevant to Canadian conditions.

It must be emphasized that these guidelines do not constitute values for uniform national water quality and that their use will require consideration of local conditions. The guidelines will also be updated as new information available.

2. MARINE AQUATIC LIFE

2.1 Recommended Guidelines

To protect aquatic life in marine environments, it is recommended that the interim maximum concentration of zinc should not exceed 10 µg Zn/L.

2.2 Summary of Existing Guidelines

For the protection of marine aquatic life, the U.S. EPA (1987) recommended that the 1-h average concentration of Zn (acid soluble) should not exceed 95 µg/L more than once every three years and the 4-d average concentration of Zn in saltwater should not exceed 86 µg/L more than once in three years. For marine waters of California, it was recommended that the concentration of Zn should not exceed a maximum of 20 µg/L in a six-month median and that 170 µg/L should not be exceeded (Klapow and Lewis 1979). No other marine guideline was found in the literature.

2.3 Rationale

The acute (and chronic) toxicity data for fish in the marine environment are limited. The available data show that the toxicity of Zn varied greatly in the marine species. Eisler and Hennekey (1977) reported a 96-h LC_{50} of 60,000 µg Zn/L for adult mummichog (*F. heteroclitus*); all fish died within 96 hours when exposed to 120,000 µg Zn/L. The 48-h LC_{50} of 96,500 µg Zn/L for mummichog by Burton and Fisher (1990) was in the range (15,000 to 180,000 µg Zn/L) reported by Eisler and Hennekey (1977).

The significant changes in the larval epidermis of *Clupea harengus* at 6,000 to 12,000 µg Zn/L are among the lowest chronic values reported in the literature (Somasundaram 1985). In a secondary ranked study, Eisler and Hennekey (1977) reported 8-day LC_{50}s for mummichog (*F. heteroclitus*) that ranged from 52,000 to 66,000 µg Zn/L.

Among invertebrates, oysters (*Crassostrea virginica* and *Crassostrea gigas*) and bryozoan (*Bugula neritina*) appeared to be the most sensitive species with 96-h LC_{50} of about 230 µg Zn/Land 5-h LC_{50} of 200 µg Zn/L, respectively (U.S. EPA 1987, Wisely and Blick 1967). However, the test conditions for these experiments were not available. Acute toxicity of Zn was also tested in other marine species. For all age groups of the mysid (*Mysidopsis bahia*), Nipper et al. (1993 a,b) reported a 96-h LC_{50} of 360 µg Zn/L. These authors also reported much lower 48-h LC_{50}s for copepod *Temora stylifera* ranging from 4 µg Zn/L at 23% salinity to 31 µg Zn/L at 32% salinity. Nipper et al. obtained their data on copepods from south-eastern Brazil. Their data (e.g., 48-h LC_{50} of 4 µg/L) were also suspect because the survival rate for the control copepod population at 23% salinity was lower than the acceptable value for toxicity tests; the percent copepod survival in the control chambers were 76% at 23% salinity and 97% at 32% salinity. Finally, Dinnel et al. (1989) reported 96-h EC_{50}s of 23 µg/L for the embryo development of green (*Strongylocentrotus droebachiensis*) and purple (*S. purpuratus*) sea urchins.

Canli and Furness (1992) conducted a study on the toxicity of heavy metals dissolved in sea water and influences of sex and size on metal accumulation and tissue distribution in the Norway lobster (*Nephrops norvegicus*). The authors concluded that there was no relationship between Zn concentration and body size, and no statistically significant difference in Zn concentrations between the sexes.

Hunt and Anderson (1989) reported 9-d EC_{50} (metamorphosis) of 50 µg Zn/Land 48-h EC_{50} (shell development) of 68 µg Zn/L for the red abalone (*Haliotis rufescens*) larvae. These investigators also reported a 9-d NOEC (no observed effect concentration) of 19 µg Zn/Land a 48-h NOEC of 39 µg Zn/L for metamorphosis and the shell development, respectively, in the red abalone embryo. In another study, Ahsanullah and Williams (1991) exposed the marine amphipod *Allorchestes compressa,* in the first instar juvenile stage, to zinc for four weeks. The minimum effect concentrations (MEC) for survival, biomass production, and weight loss were reported to be 99, 142, 148 µg Zn/L, respectively. Watling (1982) reported 96-h GC_{50}s (concentration affecting growth in 50% of the population) of 80 and 95 µg Zn/L, respectively, for the 6-d old and 16-d old larvae of the Pacific oyster *Crassostrea gigas,* suggesting that the earlier life stages are more sensitive to zinc.

Four studies reported effect levels that were among the lowest: In a study ranked primary, Dinnel et al. (1989) reported a 1-h EC_{50} of 28 µg Zn/L for sperm fertilisation of the sand dollar (*Dendraster excentricus*). Watling (1983) reported reduced level of settling in 14 days for the 51-d-old cultchless spat of Pacific oyster (*C. gigas*) exposed to 10 to 20 µg/L of zinc; however, the settling rate in the 35-d-old cultchless spat were unaffected by the Zn exposure. Inconsistency in the Zn effects was observed in other experiments; for instance, prolonged exposure to low Zn concentrations resulted in delayed settlement whereas short-term exposure to slightly higher Zn concentrations induced early settlement. For the same specie of oyster and the effect (settling characteristics of larvae), Watling (1983) reported 6-d EC_{50} ranging between 30 and 35 µg Zn/L. In tests with brine shrimp *Artemia* larvae in artificial sea water, Bagshaw et al. (1986) reported that zinc (6.5, 65, and 650 µg/L) had no detectable effect on pre-emergence of the larvae, but the number of nauplii hatched were slightly lower at 6.5 µg Zn/L (49.7%±6.1%) than the control (64.7%±7.7%). These investigators did not test statistical significance of the results; also, the tests (incubation) were conducted at fairly high temperature (28°C).

As with other organisms in the marine environment, marine algae and macrophytes showed a wide range in zinc toxicity. Marine algae (*Rhizosolenia* spp.) appeared to be the most sensitive species to the chronic effects of zinc, showing a photosynthesis reduction when exposed to 15 and 25 µg Zn/L (Davis and Sleep 1979, Spear 1981). The U.S. EPA (1987) reported a 50% reduction in the growth of the diatom (*Schoederella schroederi*) over a period of 48-96 hours when it was exposed to 19 µg Zn/L, and a 65% reduction in the chlorophyll production in dinoflagellate (*Glenodium halli*) exposed to 20 µg/L zinc for 2 days. Adverse effects were also reported by Hollibaugh et al. (1980) for the diatom (*S. costatum*) at 19.6

µg Zn/L. In a more recent study, Stauber and Florence (1990) reported a 4-d IC_{50} (for cell division) of 65 µg Zn/L for the diatom (*Nitzschia closterium*).

The recommended guideline is based on lowest observed effect (chronic) levels of 0.019-0.0196 mg/L zinc for marine alga *S. schroederi* (Kayser 1977) and *S. constatum* (Hollibaugh et al. 1980) and an application factor of 0.5. The use of the application factor of 0.5, instead of 0.1 recommended by the CCME (1991), was justified on the same grounds as for freshwater life. Also, the proposed guideline is characterised as interim, since the minimum requirement for primary data was not met.

Davis and Sleep (1979) reported a reduction in photosynthesis by a marine alga (*Rhizosolenia sp.*) exposed to 15 to 25µg/L of zinc. Also, Watling (1983) reported a reduced settlement of Pacific oyster (*C. gigas*) larvae exposed to 10-20 µg/L zinc. These data were not acceptable for the development of the Canadian Water Quality Guideline because the Watling experiments produced inconsistent results. Bagshaw et al. (1986) reported that brine shrimp exposed to 0.1 µM (6.5 µg/L) zinc had slightly reduced number of nauplii hatched in 48 hours. Their data also were not accepted because: (a) their tests were conducted at a relatively high temperature (28°C), and (b) they did not report if the observed effect was statistically significant compared to the control.

Tables 1 to 5 provide a summery of existing toxicity data for marine aquatic life.

3. <u>WILDLIFE</u>

3.1 Recommended Guidelines

Canadian water quality guideline to protect wildlife from adverse effects of zinc is not recommended due to the lack of data.

3.2 Summary of Existing Guidelines

Water quality guidelines to protect wildlife from adverse effects of zinc were not found in the literature.

3.3 Rationale

Limited information on zinc toxicity to wildlife was found in the literature.

Mallard and Pekin ducks (*Anas* spp.) showed reduced survival when exposed to 2 500-3 000 mg Zn/kg in diet or when forced-fed zinc metal shot equivalent to 742 mg Zn/kg body weight (bw) (Eisler 1993, Grandy et al. 1968). Wobeser (1981) noted that mallards (*A. platyrhynchos*) poisoned with force-fed zinc shot pellets developed ataxia, paresis, and total loss of muscular control of legs, including the ability to swim. The muscular weakness associated with zinc intoxication would probably make ducks highly susceptible to predation (Grandy et al. 1968). Mallards fed 3 000 mg Zn/kg diet (dry weight) for 60 days had diarrhea after 15 days, leg paralysis in 20 days and high mortality after 30 days (Gasaway and Buss 1972).

In Australia, almost all aviary birds held in cages of galvanized wire mesh displayed signs of “new wire disease” caused by the ingestion of galvanized metal. In one case, Reece et al. (1986) found that peach-faced lovebirds (*Agapornis roseicollis*) died within 5 weeks of placement in a newly erected wire cage; dead birds had elevated liver zinc concentrations of 75- 156 mg/kg dry weight versus normal values of 21-33 mg/kg dry weight.

Guthrie (1971) reported that Japanese quail (*Coturnix coturnix japonica*), injected intra-testicularly with 3% $ZnCl_2$ equivalent to 1 mg Zn/kg testes or 0.02 mg/kg bw, developed testicular teratomas during a period of testicular growth stimulated by photoperiod. The safe level of 25-30 mg Zn/kg in diet (dry weight) to prevent zinc deficiency in Japanese quail has been recommended by Harland et al. (1975) in their study.

4. IRRIGATION

4.1 Recommended Guidelines

It is recommended that the concentration of total zinc in irrigation water supplies should not exceed 1.0 mg/L for soils with pH <6, 2.0 mg/L for soils with pH ranging between 6.0 and 7.0, and 5.0 mg/L for soil with pH of 7.0. This guideline replaces the 1987 CCREM guidelines of 1.0 Zn mg/L for continuous use on soils below pH 6.5, and 5.0 mg Zn/L at higher pHs.

4.2 Summary of Existing Guidelines

The CCREM (1987) recommended that the concentration of total zinc in irrigation waters should not exceed 1.0 mg/L for continuous use on soils below pH 6.5. At higher pH, CCREM recommended a limit of 5.0 mg/L. These limits were based on a the rep01t published by Taylor and Demayo (1980). Assuming adequate use of liming material to keep soil pH values high (pH 6 or above), the U.S. EPA (1973) recommended a maximum concentration of 2.0 mg/Lin irrigation water for continuous on all soils. For a 20-year period on neutral or alkaline soils, the recommended concentration in irrigation water is 10 mg/L zinc. Ontario (OMOE 1984) and Manitoba (Williamson 1988) also recommended these limits.

4.3 Rationale

Zinc is an essential element for plant growth. Plant growth can suffer from lack of zinc in zinc-deficient soils. At the other end of the spectrum, excessive levels of zinc in soils are toxic to plants and soil organisms. For instance, zinc toxicity has been observed in cotton and soybean (Lee and Craddock 1969) and in peanut (Keisling et al. 1977) exposed to Zn in pesticide sprays used in peach (cotton and soybean) and pecans (peanut) production. Phytotoxicity of zinc has also been observed in sludge-treated soils (Williams 1980, Berrow and Bridge 1990) and in ecosystems subjected to emissions from zinc and other metal smelters (Beyer 1988, Chaney et al. 1988).

Several soil (pH, texture, redox potential), plant (cultivar, species), and environmental (temperature, presence of and interaction with other metals; form of zinc) factors influence zinc availability and toxicity to plants. Zinc is most soluble in acid soils. The solubility of zinc, hence its availability to plants, decreases as soil pH is increased from pH 4 to pH 7. Parker et al. (1990) found that an increase in soil Zn from 1.0 to 10 mg/kg increased peanuts leaf Zn by 202 mg/kg at soil pH 4.6 and by only 9 mg/kg at pH 6.6. In sewage sludge-treated soils, Williams (1980) observed a reduction in the metal phytotoxicity when soil pH was raised from 6.2 to 7.0. At pH 7.0, more than four times the quantities of zinc and nickel were required to produce the same reduction in yield of red beet and onions as at pH 6.2. In a more recent study, Smith (1994) noted that concentrations of all the elements (nickel, copper, and zinc) in rye grass, grown on two sludge-treated soils, decreased as simple linear functions of increasing soil pH from 4.2 to 7.0. Based on these results, Smith (1994) proposed maximum permissible concentrations of zinc in soil as a function of pH, to protect against phytotoxic reactions. Strongly reducing conditions in flooded soils, high specific Zn absorption capacity of heavy textured soils, and high organic content of soils, tend to reduce Zn availability and phytotoxicity (Adriano 1986, Sanders et al. 1987, Chaney 1993).

Plants differ widely in their susceptibility to soil zinc. In acid soils, most grasses are relatively more tolerant to zinc than most dicots, but this order is reversed in alkaline soils (Chaney 1993). Sanders et al. (1987) found that the threshold for yield reduction was lower for red beet (a dicot; 90 mg Zn/kg leaf) than for white clover (a grass, 400 mg Zn/kg leaf). Cultivars of a single plant species also show similar differences in their ability to accumulate and tolerate zinc (Adriano 1986). Some plants exhibit extreme tolerance to excessive zinc in soil. Zn tolerant ecotypes of several species have been selected at mine sites in several nations (Baker 1987, Antonovics et al. 1971). Genes for Zn tolerance exist in natural populations of many forage species (Walley et al. 1974).

The fundamental biochemical mechanism of Zn phytotoxicity has not been identified as yet (Chaney 1993). Nevertheless, a variety of plant responses manifest zinc phytotoxicity. Chlorosis is common in species exposed to high concentrations of Zn in acid soils. Spraying of $FeSO_4$ or chelated Fe on the leaves corrects chlorosis, indicating that Zn has interfered with Fe uptake. Other plant responses include production of metal-binding peptides and induction of certain enzymes. Van Assche et al. (1988) and Clijsters et al. (1984) found that the leaf enzyme activity in dwarf beans (*Phaseolus vulgaris* L.) increased with exposure to zinc. The threshold values were similar for shoot growth inhibition (226 mg Zn/kg leaf) and enzyme capacity induction (227±26 Zn mg/kg leaf). Fontes and Cox (1993) observed that zinc toxicity induces synthesis of low molecular weight Zn-binding peptides in soybean (*Glycine max* L.) roots and leaves. As yet, it is not clear if activities of enzymes or metal binding peptides can be used as criterion for heavy metal toxicity before visible damage is observed.

Zinc can also be toxic to soil organisms. Spurgeon et al. (1994) exposed earthworm *Eiseniafetida* to zinc in an artificial soil (70% sand, 20% kaolin clay. and 10% organic matter as *Sphagnum* peat). Mortality, growth, and cocoon production were measured over a period of 56 days. The average 14-d LC_{50} was estimated to be 1,010 mg Zn/kg soil. Cocoon production was a more sensitive endpoint with a 56-d EC_{50} of 276 mg Zn/kg soil. However, these investigators noted that the overall cocoon production rates for the experiment were low due probably to the lack of suitable food in the artificial soil. Nevertheless, the viability of cocoons (i.e., the proportion from which juveniles emerged) was high (>88%) in all samples. These investigators also noted that the test procedure required modification if it is to be used for longer term toxicity studies.

Donkin and Dusenbury (1994) measured toxicity of Zn to soil nematodes *Caenorhabditis elegans.* An average LC_{50} of 255 mg Zn/kg soil was reported for the organism in Worsham sandy loam with pH 5.1. Furthermore, the LC_{50} increased as the clay content of the soils increased. These investigators also concluded that the soil toxicity test with *C. elegans* was as sensitive and more rapid than the commonly used earthworm soil toxicity test.

The effect of zinc on microbial biomass and nitrogen fixing bacteria has been the subject of several investigators. Giller et al. (1989) and Chaudri (1992) observed that the long-term metal stress in a contaminated soil resulted in the death of effective rhizobia (*Rhizobium Leguminosarum* bv, *trifoli*); also, only the metal tolerant rhizobia survived which had lost their ability to fix atmospheric nitrogen. These authors also concluded that Zn and cadmium were the most toxic metals to trofolii and ranked the order of toxicity as Cd>Zn>Cu>Ni. In their well controlled field experiments, Chaudri et al. (1993) noted that the reductions in the nitrogen content, chlorosis and stunting of clover plants were not due to the metal phytotoxicity, but due to nitrogen deficiency resulting from a lack of nitrogen fixation. The zinc concentration at which rhizobia numbers declined significantly compared to the control plots ranged from 200- 250 mg/kg soil. Chander and Brookes (1993) and Lieta et al. (1995) reported reduction in microbial biomass in metal-contaminated soils; the threshold concentration and the concentration that caused 46% reduction in the biomass were 375 mg Zn/kg soil and 600 mg Zn/kg soil, respectively.

Metal contamination is generally a multi-element problem in the environment. This is a most common occurrence where sewage sludge, metal mining waste, or dredged material are disposed to land. The presence of other contaminants simultaneously may modify uptake and phytotoxicity of zinc. Luo and Rimmer (1995) found that the effect of added copper to soil increased the uptake and toxicity of added zinc to spring barley (*Hordeum vulgare*) in a greenhouse environment (synergistic effect). In an earlier study, Beckett and Davis (1978) reported an antagonism in Cu and Zn effects (reduction in zinc uptake by copper) in his experiment using nutrient solution. Obviously, a comparison of soil and culture solution experiments requires careful attention. Studying the effect of metal sludges on microbial biomass, Chander and Brookes (1993) found 12% less biomass than control in soils containing either 420 mg Zn/kg or 196 mg Cu/kg separately. In contrast, the soils containing Cu and Zn together, but at lower rates (191 mg Cu/kg and 367 mg Zn/kg), had 29% less biomass than the control.

Many investigators have used laboratory experiments to study plant uptake and phytotoxicity of zinc. deVries and Tiller (1978) reported that Zn uptake by lettuce in greenhouse pot experiments was about 4-times higher than that found in the field. Factors such as restriction of all roots to the contaminated soil, and generally higher soil temperature and transpiration rates may contribute to such behaviour (Chaney 1993). No reports were found that compared phytotoxic levels of Zn in the field and laboratory environments.

Adding zinc salts such as $ZnSO_4$ acidifies soils as the Zn displaces protons from the adsorption surf aces. Even when soil pH was brought to the same level as other Zn treatments by addition of $CaCO_3$, White and Chaney (1980) found that added Zn salts increased manganese (Mn) uptake by soybeans. Also, the phytotoxic reaction of the soybeans was a result of both Zn and Mn. However, in field studies where soil pH stayed at 5.5 or above and was equal among treatment, added sludge Zn did not increase Mn uptake by plants. Chaney et al. (1990) obtained similar results (no increase in plant Mn with increasing added Zn) in pot studies at pH> 5.5. In studying extractability of soil Zn with $CaCl_2$ extract, Chander and Brookes (1993) found that 42% of the soil Zn was available from the sludged soils whereas only 3% was available from soils that never received sewage sludge.

Several jurisdictions have proposed safe limits of zinc (and other metals) in soils to control the application of metal-contaminated sludges; these safe limits are often expressed as a function of pH (Smith 1994, Chaudri et al. 1993). The plots of data gathered from the literature showed that zinc toxicity can be expressed as a function of soil pH with the maximum toxicity occurring below pH 6, intermediate toxicity in the mid pH range of 6-7, and the minimum toxicity at pH 7. The mean toxic concentrations of zinc in soils (geometric mean of LOEC and NOEC) estimated from the data were use for deriving the proposed irrigation water quality guidelines as a function of soil pH.

The recommended water quality guidelines are based on the lowest observed effect concentrations (LOECs) of 66 mg Zn/kg soil at pH< 6.0, 132 mg Zn/kg soil at pH 6 to< 7.0 (Lyszcz and Ruszkowska 1992), and 319 mg Zn/kg soil at pH 7.0 (Davis and Carlton-Smith 1984). Since the no observed effect concentrations (NOEC) were not quoted by the investigators, they were estimated using the relationship NOEC = LOEC ÷ 4.5, as suggested by the CCME (1993) protocol. Based on these data, acceptable soil concentrations (ASC) for the three pH intervals were calculated as follows (CCME 1993):

ASC= $[66 \times (66 \div 4.5)]^{0.5} \div 10$ = 3.11 mg Zn/kg soil at pH < 6.0;

ASC= [132 × (132÷4.5)]0 5 ÷ 10 = 6.22 mg Zn/kg soil at pH 6.0 to < 7.0;

ASC= $[319 \times (319 \div 4.5)]^{0.5} \div 10$ = 15.0 mg Zn/kg soil at pH >7.0;

Assuming a leaching depth of 0.3 m, the species maximum acceptable toxicant concentrations (SMATC) or the Canadian water quality guidelines (CWQG) for irrigation waters were calculated as follows (CCME 1993):

= (3.11 mg Zn/kg soil) (1300 kg/m3) (100 x 100 x 0.3 m 3 / ha) ÷ (1.2 × 107 L/ha), or

= 1.0 mg Zn/L (rounded to a single digit) for soils with pH<6.0

= (6.22 mg Zn/kg soil) (1300 kg/m3) (100 x 100 x 0.3 m 3 / ha) ÷ (1.2 × 107 L/ha), or

= 2.0 mg Zn/L (rounded to a single digit) for soils with pH 6.0 to <7.0

= (15 mg Zn/kg soil) (1300 kg/m3) (100 x 100 x 0.3 m 3 / ha) ÷ (1.2 × 107 L/ha), or

= 5.0 mg Zn/L (rounded to a single digit) for soils with pH 37.0

In the above calculations, the leaching depth of 0.30 m, instead of 0.15 m as recommended by the CCME protocol, was used because (a) root zone for many irrigated crops extends beyond 15 cm depth and (b) zinc is relative mobile in soil as compared to other heavy metals. In soils (silty clay loam to clay in texture) irrigated with liquid raw sewage, Leeper (1978) found that zinc moved considerably below (25-45 cm) a depth of 18 cm.

Takkar and Mann (1978) reported that zinc concentration as low as 50 mg Zn/kg soil was toxic to wheat. The toxic concentration of 50 mg Zn/kg soil was the lowest of all available data. Nevertheless, the Takkar and Mann data were not used in deriving the irrigation water quality guidelines because these investigators did not specify soil pH.

Table 7 and Figure 1 provide a summary of LOECs and NOECs of zinc on agricultural crops and soil organisms. Along with the recommended WQG.

5. LIVESTOCK WATERING

5.1 Recommended Guidelines

A Canadian water quality guideline of 2 mg/L zinc is recommended to protect livestock water use. This guideline replaces the CCREM (1987) guideline for livestock watering of 50 mg/L zinc.

5.2 Summary of Existing Guidelines

The CCME, in its document published in 1987 (CCREM 1987), recommended that the concentration of zinc in water used for livestock watering should not exceed 50 mg/L. The maximum concentration of 50 mg Zn/L for the livestock watering was also recommended by the Province of Manitoba (Williamson 1988). The recommended limits for livestock watering are 2.5 times lower in Australia (20 mg Zn/L- Hart 1984) and 2.0 times lower in the United States and Ontario (25 mg/L- OMOE 1984, U.S. EPA 1973).

5.3 Rationale

A considerable amount of data was available in the literature on zinc deficiency and toxicity to livestock and other animals. The most recent review on the subject was conducted by Eisler (1993). The following discussion is based on the Eisler’s review and includes additional information found in the literature.

Zinc is involved in a multitude of physiological functions and, therefore, is an essential trace mineral for normal growth and development of biota. For instance, zinc deficiency in mammals may adversely affect metabolism of DNA, RNA, proteins, and activity of carbonic anhydrase, lactic dehydrogenase, mannosidase, and other enzymes. Zinc deficiency in chickens, turkeys, and Japanese quails is characterised by low survival, reduced growth rate, poor feathering, shortening and thickening of long bones of legs and wings, reduced egg production and hatchability, skeletal deformities in embryos, an uncoordinated gait, and increased susceptibility to infection. The potentially severe effects of zinc deficiency in birds and animals have been documented by several investigators (Tucker and Salmon 1955, Miller 1980, Graham et al. 1987a and b, NAS 1980, Eisler 1993). Compared with zinc toxicity, zinc deficiency is much more frequent risk to mammals (Leonard and Gerber 1989).

Zinc can be toxic to animals if administered in high doses. However, there is a wide margin of safety in zinc supplementation of feeds for animals (NAS 1980). Reviewing the literature on Zn toxicosis, Graham et al. (1987b) noted that dietary zinc supplementation used to increase rates of gain and feed efficiency and to prevent foot rot in sheep and infectious pododermatitis in cattle can result in death, fetal loss, or reduced performance. These authors also studied mortality in veal calves (3- to 6-month-old male Holstein) subsequent to an episode of Zn toxicosis on a veal calf operation using $ZnSO_4$-supplemented milk replacer. Clinical signs were clearly apparent after calves were exposed to 1.5 to 2.0 g Zn/d, or approximately 14 to 15 mg Zn/kg body weight/d (from a milk replacer containing 706 µg Zn/g of milk replacer).

Graham et al. (1987 a, b) suggested that concentration of Zn should not exceed 100 µg/g of diet in preruminants (this may also apply to ruminating cattle) unless a zinc deficient state exist or additional research determines a need for supplementation greater than 100 µg/g diet for improved performance.

Smith et al. (1979) reported that acute death was unlikely in the 11-month-old sheep fed zinc at the rate of 50 mg/kg bw/d for 3 weeks. On the other hand, Graham et al. (1987 a, b) found that a feeding rate of as low as 14 to 15 mg Zn/kg bw/d (mostly from milk replacer diet) caused mortality in the calves after 25 days. The lack of acute intoxication in the Smith et al. sheep was probably due to the presence of functional rumen. Ruminants may have a greater capacity to metabolize zinc than nonruminant animals and/or more complexing of zinc may develop in animals on roughage diet than in those on milk replacer. Graham et al. further suggested that concentrations of zinc should not exceed I00 mg/kg of diet in preruminants unless a zinc deficient state exists. In a later study Smith and Embling (1993) exposed IO-month-old sheep three times per week to 240 mg Zn (as ZnO)/kg bw/dose for 4 weeks. Although no animals showed any clinical signs of zinc toxicity, many sheep dosed with zinc oxide developed pancreatic lesions.

In studying tolerance of preruminant calves for excess zinc in milk replacer (a 5-week study), Jenkins and Hidiroglou (1991) reported no adverse effect on the performance of the calves exposed to 500 mg/kg zinc in milk replacer, a concentration that is markedly higher than the NRC (1989) recommendations of 40 mg Zn/kg diet. However, zinc concentrations increased in some tissues in response to the exposure which indicated that toxicity might have arisen if the trial had been continued. These investigators suggested that there was no evidence of benefits to the calves from Zn intakes above the NRC recommendations.

Dean et al. (1991) reported depressed body weight in broiler chicks (200-day-old males) exposed to 2 580 mg Zn/kg in diet as compared to the control population fed diet containing 73 mg Zn/kg. The impaired growth was independent of feed consumption and was accompanied by reduced levels of serum cholesterol, high-density lipoprotein cholesterol, and growth hormone. Stahl et al. (1989, 1990) also reported that chicks were unaffected by dietary zinc at dietary levels of 28 (control), 48, 100, and 228 mg Zn/kg; however, reduced growth rate, anaemia, decrease in tissue copper and iron, and increase in tissue zinc levels were evident in chicks fed over 2,000 mg Zn/kg in diet for 21 days.

The assumptions and procedure used in the derivation of the livestock watering guideline are as follows:

1. Young calves (100 kg) are more sensitive to zinc toxicity than mature cattle. For normal growth, the concentration of 70 mg Zn/kg in diet (dry matter) was assumed to be safe. This is an average value of the levels recommended by Graham et al. (100 mg Zn/kg diet - 1987a, b) and Jenkins and Hidiroglou (40 mg Zn/kg diet - 1991). It is also within the normal growth limits of zinc in diet

recommended by Puls (50-100 mg Zn/kg diet - 1981). Although, much higher levels of zinc in diet can be tolerated, no evidence exists indicating that calves will benefit from zinc intakes above those required for normal growth (Jenkins and Hidiroglou 1991.).

2. Cattle, when fed liberally, consume dry matter per day on the average of 2.5% of their body weight (bw) (Agriculture Canada 1981a). At this rate, a young calf will consume= (0.025 kg feed/kg bw/d) × (70 mg Zn/kg feed), or= 1.75 mg Zn/kg bw/day for normal growth. Based on these calculations, the tolerable daily intake (TOI) was assumed to be 1.75 mg Zn/kg bw/d for livestock.
3. Graham et al. (1987b) reported clinical signs in calves (75 kg bw) exposed to 14 to 15 mg Zn/kg bw/d for 23 days. Applying an uncertainty factor of 10 to these values, as recommended by the CCME (1993), will yield a 'IDI which is comparable to that in step 2 (The Graham et al. results were not used in the calculation of required TOI as recommended by the CCME (1993) protocol, because their results were influenced to some degree by some predisposing factors relating to age of the animal, previous pneumonia severity, environment, and cumulative amount of zinc consumed).
4. A young calf (100 kg bw) will consume 2.5 kg of dry matter (dm) per day (see step 2). Assuming water intake of 6.5L/kg diet (feed dry matter or dm) for calves (Agriculture Canada 1981b), the daily water intake (WIR) of the calves was calculated to be:

   WIR = 2.5 × 6.5 = 16.25 L/d.

5. Using the CCME (1993) protocol, the reference concentration (RC) was, then, calculated as below:

   RC (mg/L) = TDI (mg/kg bw/d) × bw (kg) ÷ WIR (L/d)

   or RC = 1.75 × 100 ÷ 16.25 = 10.8 mg/L

6. Given that drinking water contributes 20% of the livestock Zn requirement (CCME 1993), the Canadian water quality guideline (CWQG) for zinc in livestock watering was computed as below:

   CWQG = 10.8 × 0.2 =2 mg/L (rounded to a significant digit)

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Table 1. Acute toxicity of zinc to marine fish

Species	Life Stage	Type of data	Chemical	pH	D.O., (mg/L)	Temp. (°C)	Salinity (‰)	Conc. (mg/L)	Effect	Reference
Fundulus heteroclitus (mummichog)	adult~1.30 g wet	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	15	LC0-96 hr	
	adult~1.30 g wet	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	60	LC50-96 hr	
	adult~1.30 g wet	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	120	LC100-96 hr	
	adult~1.30 g wet	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	15	LC0-24 hr	
	adult~1.30 g wet	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	125	LC50-24 hr	
	adult~1.30 g wet	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	180	LC100-24 hr	
	juvenile <23 days	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	96.5	LC50-48 hr	Burton & Fisher 1990

*This data was obtained from a secondary source and, therefore, could not be assessed. The acute concentrations could have been obtained in a freshwater environment

KEY

LC = Lethal Concentration	M=Measured
1 =Primary	N=Nominal
2 =Secondary	NA= Not Available
S = Static Test Method	F = Flowthrough Test Method

Table 2. Chronic toxicity of zinc to marine fish

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Alkalinity/ hardness mg/L	Conc. (mg/L)	Effect	Reference
Clupea harengus	larvae	S,N,2	$ZnSO_4$	7.5	-	8	21	-	2	no significant changes in larval epidermis	Somasundaram 1985
	larvae	S,N,2	$ZnSO_4$	7.5	-	8	21	-	6	significant changes in larval epidermis	
	larvae	S,N,2	$ZnSO_4$	7.5	-	8	21	-	12	significant changes in larval epidermis	
Funulus heteroclitus (mummichog)	adult ~1.30 g wet	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	-	10	LC0-168 hr	Eisler & Hennekey 1977
	adult ~1.30 g wet	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	-	52	LC50-168 hr	
	adult ~1.30 g wet	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	-	120	LC100-168 hr	
	-	S,M,2	-	-	-	-	-	-	52-66	LC50-8 days	Eisler & Hennekey 1977; Eisler 1977

KEY

LC = Lethal Concentration	M=Measured
S = Static Test Method	N=Nominal
F = Flowthrough Test Method	NA =Not Available
	1 = Primary
	2 = Secondary

Table 3. Acute toxicity of zinc to marine invertebrates

Species	Life Stage	Chemical	Data Type	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
Acartia lilljeborgi (copepod)	adult	$ZnSO_4$	S,N,2	-	-	25	33.5	0.37	LC50-48 hr	Nipper et al. 1993
	adult	$ZnSO_4$	S,N,2	-	-	25	28	0.55	LC50-48 hr	
	adult	$ZnSO_4$	S,N,2	-	-	25	25	0.7	LC50-48 hr	
	adult	$ZnSO_4$	S,N,2	-	-	25	23	0.8	LC50-48 hr	
	adult	$ZnSO_4$	S,N,2	-	-	25	32	0.89	LC50-48 hr	
Acartia tonsa (copepod)	-	-	NA	-	-	-	-	0.294	LC50-96hr	EPA 1987
Allorchestes compressa (amphipod)	-	$ZnCl_2$	F,M,1	7.8	97%	20.3	34.l	2	LC50-96hr	Ahsanullah et al. 1988
Argopecten irradians (bay scallops)	21.2mm (av.)	$ZnCl_2$	S,N,2	6.9-7.5	-	20	25	1.2	LC5-96 hr	Nelson et al. 1988
	21.2mm (av.)	$ZnCl_2$	S,N,2	6.9-7.5	-	20	25	2.25	LC50-96hr	
	21.2mm (av.)	$ZnCl_2$	S,N,2	6.9-7.5	-	20	25	4.2	LC95-96 hr	
Asterias forbesi (starfish)	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	10	LC0-96 hr	Eisler & Hennekey 1977
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	39	LC50-96hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	300	LC100-96 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	300	LC0-24 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	390	LC50-24 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	500	LC100-24hr	
Bugula neritina (bryozoan)	larvae	-	F,M,1	-	-	-	-	0.2	LC50-5 hr	Wisely and Blick 1967
Cancer magister (dungeness crab)	zoea I stage larvae	$ZnSO_4$	S,M,2	8.1	6.5-8.0	-	33.79	0.456	LC50-96hr	Martin et al. 1981
	zoea larvae	$ZnCl_2$	F,M,1	8.1	-	8.5	20	0.586	EC50-96 hr (movement)	Dinnel et al. 1989
Carcinus maenus	larvae (1-5 days)	$ZnSO_4$	S,N,2	8.1	-	8.5	20	1	ET50-47 hr	Connor 1972
	larvae (1-5 days)	$ZnSO_4$	S,N,2	8.1	-	8.5	20	3.3	ET50-8 hr	
	larvae (1-5 days)	$ZnSO_4$	S,N,2	8.1	-	8.5	20	10	ET50-1.1 hr	
	larvae (1-5 days)	$ZnSO_4$	S,N,2	8.1	-	8.5	20	33	ET50-0.22 hr	
	larvae (1-5 days)	$ZnSO_4$	S,N,2	8.1	-	8.5	20	100	ET50-0.22 hr	
	adult	$ZnSO_4$	S,N,2	-	-	15	-	14.5	ET50-48 hr	
Clibanarius olivaceus (hermit crab)	larvae	-	NA	-	-	-	-	0.1	LC50-96 hr	Ajmalkhan et al. 1986
	larvae	-	NA	-	-	-	-	0.125	LC100-96 hr	
Crassostrea cucullate	3days	-	S,N,2	-	-	22-23	34	>0.1	LC50-96 hr	Watling 1982
	13 days	-	S,N,2	-	-	22-23	34	>0.1	LC50-96 hr	

Species	Life Stage	Chemical	Data Type	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
(oyster)										
Crassostrea gigas (Pacific oyster)	6 days	-	S,N,2	-	-	22-23	34	>0.1	LC50-96 hr	
	16 days	-	S,N,2	-	-	22-23	34	>0.1	LC50-96 hr	
	larvae	-	NA	-	-	-	-	0.119-0.310	LC50-48 hr	EPA 1980; Hunt & Anderson 1989
	embryo	-	NA	-	-			0.233	LC50-96 hr	EPA 1987
	larvae	$ZnSO_4$	S,N,2	-	-	20-22	29	0.5	LC100-48 hr	Brereton et al. 1973
Crassostrea margaritacea (oyster)	3days	-	S,N,2	-	-	22-23	34	>0.1	LC50-96 hr	Watling 1982
	13 days	-	S,N,2	-	-	22-23	34	>0.1	LC50-96 hr	
Crassostrea virginica (American oyster)	embryo	$ZnCl_2$	S,N,2	7.0-8.5	-	26	25	0.075	LC0-48 hr	Calabrese et al. 1973
	embryo	$ZnCl_2$	S,N,2	7.0-8.5	-	26	25	0.31	LC50-48 hr	
	embryo	$ZnCl_2$	S,N,2	7.0-8.5	-	26	25	0.5	LC100-48 hr	
	-	-	NA	-	-	-	-	0.23	LC50-96 hr	EPA 1987
	larvae	-	F,M,1	-	-	-	-	0.34	LC50-48 hr	Hunt & Anderson 1989
Dendraster excentricus (sand dollar)	sperm	$ZnCl_2$	F,M,1	-	-	-	-	0.0284*	EC50-1 hr (fertilization)	Dinnel et al. 1989
	embryo	$ZnCl_2$	F,M,1	8.0-8.1	-	12.5-13.0	30	>0.58	EC50-96 hr (development)	
Homarus americanus (America Lobster)	larvae		NA					0.381	LC50-96 hr	EPA 1987
Loligo opalescens (squid)	larvae	$ZnCl_2$	F,M,1	8.1		8.6	30	>1.92	EC50-96 hr (movement)	Dinnel et al. 1989
Mya arenaria (softshell clam)	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	5	LC0-96 hr	Eisler & Hennekey 1977
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	7.7	LC50-96 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	25	LC100-96 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	200	LC0-24 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	320	LC50-24 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	500	LC100-24 hr	
	adult	ZnCJ2	S,N,2	7.95	>4.0	22	30	3	LC0-96hr	Eisler 1977
	adult	$ZnCl_2$	S,N,2	7.95	>4.0	22	30	5.2	LC50-96 hr	
	adult	$ZnCl_2$	S,N,2	7.95	>4.0	22	30	9	LC100-96hr	
	adult	ZnCJ2	S,N,2	7.95	>4.0	22	30	30	LC0-48 hr	
	adult	$ZnCl_2$	S,N,2	7.95	>4.0	22	30	52	LC50-48 hr	
	adult	ZnCJ2	S,N,2	7.95	>4.0	22	30	90	LC100-48 hr	

Species	Life Stage	Chemical	Data Type	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
Mysidopsis bahia (mysid)	post-larvae (24 d)	$ZnCl_2$	F,M,1	7.8-8.2	-	23	30	0.499	LC50-96 hr	Lussier et al. 1985
Mysidopsis juniae (mysid)	1 day	$ZnSO_4$	S,N,2	-	-	25	33.5	0.35	LC50-96 hr	Nipper et al. 1993
	1 day	$ZnSO_4$	S,N,2	-	-	25	33.5	0.34	LC50-96hr	
	2days	$ZnSO_4$	S,N,2	-	-	25	33.5	0.37	LC50-96 hr	
	3 days	$ZnSO_4$	S,N,2	-	-	25	33.5	0.36	LC50-96 hr	
	3 days	$ZnSO_4$	S,N,2	-	-	25	33.5	0.38	LC50-96hr	
	5 days	$ZnSO_4$	S,N,2	-	-	25	33.5	0.35	LC50-96 hr	
	all age groups	$ZnSO_4$	S,N,2	-	-	25	33.5	0.36	LC50-96 hr calculated	
Mytilus edulis (mussel)		-	S,N,2	-	-	12	-	20.8	LC50-24hr	Hietanen et al. 1988
	~0.223g dry	-	S,N,2	-	-	15.5	35	>5.0	LC50-96 hr	Amiard-Triquet et al. 1986
	larvae	-	F,M,1	-	-	-	1.752	-	LC50-48 hr	Hunt & Anderson 1989
Nassarius obsoletus (snail)	adult	ZnCl2	S,M,2	7.8	>4.0	20	20	10	LC0-96 hr	Eisler & Hennekey 1977
	adult	ZnCl2	S,M,2	7.8	>4.0	20	20	50	LC50-96 hr	
	adult	ZnCl2	S,M,2	7.8	>4.0	20	20	300	LC100-96hr	
	adult	ZnCl2	S,M,2	7.8	>4.0	20	20	50	LC0-24 hr	
	adult	ZnCl2	S,M,2	7.8	>4.0	20	20	150	LC50-24 hr	
	adult	ZnCl2	S,M,2	7.8	>4.0	20	20	300	LC100-24 hr	
Nereis virens (sandworm)	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	4.5	LC0-96 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	8.1	LC50-96 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	15	LC100-96 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	4.5	LC0-24 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	20	LC50-24 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	30	LC100-24 hr	
Pagarus longicarpus (crab)	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	0.1	LC0-96 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	0.4	LC50-96 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	5	LC100-96 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	5	LC0-24 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	12	LC50-24 hr	
	adult	$ZnCl_2$	S,M,2	7.8	>4.0	20	20	30	LC100-24 hr	
Palaemonetes pugio (grass shrimp)	juvenile <20 mm	$ZnCl_2$	S,M,2	7.8	>40%	20	10	11.3	LC50-48 hr	Burton & Fisher 1990
Perna virdis	adult	-	NA	-	-	-	-	6.09	LC50-96 hr	Chan, 1988

Species	Life Stage	Chemical	Data Type	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
(Green-lipped mussel)										
Scorpaenichthys marmoratus (cabezon)	larvae	$ZnCl_2$	F,M,1	7.9	-	8.3	27	0.191	EC50-96 hr (movement)	Dinnel et al. 1989
Spisula solidissima (surf clam)	15.9 mm (av.)	$ZnCl_2$	S,N,1	6.9-7.5	-	20	25	2.95	LC50-96 hr	Nelson et al. 1988
	15.9 mm (av.)	$ZnCl_2$	S,N,1	6.9-7.5	-	20	25	4.8	LC95-96 hr	
Strongylocentrotus droebachiensis (green sea urchin)	embryo	$ZnCl_2$	F,M,1	7.8-8.1	-	8.2-8.4	30	>0.027	EC50-96 hr (development)	Dinnel et al. 1989
	sperm	$ZnCl_2$	F,M,1	-	-	-	-	0.383	ECS0-1 hr (fertilization)	
S. franciscanus (red sea urchin)	sperm	$ZnCl_2$	F,M,1	-	-	-	-	0.313	EC50-1 hr (fertilization)	
S. purpuratus (purple sea urchin)	embryo	$ZnCl_2$	F,M,1	7.8-8.1	-	8.2-8.4	30	0.023	EC50-96 hr (development)	
	sperm	$ZnCl_2$	F,M,1	-	-	-	-	0.262	EC50-1 hr (fertilization)	
Temora stylifera (copepod)	adult	$ZnSO_4$	S,N,2	-	-	25	23	0.004	LC50-48 hr	Nipper et al. 1993
	adult	$ZnSO_4$	S,N,2	-	-	25	28	0.023	LC50-48 hr	
	adult	$ZnSO_4$	S,N,2	-	-	25	25	0.03	LC50-48 hr	
	adult	$ZnSO_4$	S,N,2	-	-	25	32	0.031	LC50-48 hr	
	adult	$ZnSO_4$	S,N,2	-	-	25	33.5	0.044	LC50-48 hr	
Tisbe holuthuriae (copepod) (fed)	copepodids (7-d nauplii)	$ZnSO_4$	S,N,2	-	-	-	-	0.421	LC50-48 hr	Verriopoulos & Moraitou-Aoostolooooulou 1980
	adult females with first egg	$ZnSO_4$	S,N,2	-	-	-	-	0.713	LC50-48 hr	
	adult females with ovigerous bands	$ZnSO_4$	S,N,2	-	-	-	-	0.783	LC50-48 hr	
	adult females with first egg	$ZnSO_4$	S,N,2	-	-	-	-	1.076	LC50-48 hr	
	female (12-d old)	$ZnSO_4$	S,N,2	-	-	-	-	1.15	LC50-48 hr	
(fed ulva)	-	-	S,N,2	-	-	-	-	10	52.4% dead- 2 d	
	-	-	S,N,2	-	-	-	-	200	100% dead- 4 d	
	-	-	S,N,2	-	-	-	-	1000	100% dead- 2 d	
Watersipora cucullata	larvae	-	F,M,1	-	-	-	-	0.65	LC50-5 hr	Wisely and Blick 1967

Species	Life Stage	Chemical	Data Type	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
(bryozoan)										

KEY

LC == Lethal Concentration	F= Flowthrough Test Method	N=Nominal
EC= Effective Concentration	ET = Effective Time	NA= Not Available
S = Static Test Method	M = Measured	1 = Primary; 2 = Secondary

Table 4. Chronic toxicity of zinc to marine invertebrates

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
Acartia tonsa (copepod)	-	NA	-	-	-	-	-	0.29	50% immobilization 48 hr	EPA 1980
Allorchestes compressa (marine amphipod)	first instar juveniles	F,M,1	$ZnSO_4$	8	6.9	19	31	0.099	MEC-4 weeks (survival)	Ahsanullah & Williams 1991
	as above	F,M,1	$ZnSO_4$	8	6.9	19	31	0.142	MEC-4 weeks (biomass)	
	as above	F,M,1	$ZnSO_4$	8	6.9	19	31	0.148	MEC-4 weeks (weight)	
Argopecten irradians (bay scallop)	larvae	NA	-	-	-	-	-	0.05	EC22 -9 days (growth rate)	Yantian 1989
	larvae	NA	-	-	-	-	-	0.109	EC22 -9 days (growth rate)	
	larvae	NA	-	-	-	-	-	0.12	LC50-9 days	
	larvae	NA	-	-	-	-	-	0.150-0.200	All dead at metamorphosis	
Artemia (brine shrimp)	embryo	S,N,2	$ZnCJ_2$	-	-	28	-	control	E24= 8.7 H24= 56.1 E48=5.1 H48=64.7**	Bagshaw et al. 1986
	embryo	S,N,2	$ZnCJ_2$	-	-	28	-	0.1µM (1*)	E24=31.8 H24=24.1 E48=22.3 H48=49.7	
	embryo	S,N,2	$ZnCJ_2$	-	-	28	-	1µM	E24=51.7 H24=12.9 E48=40.2 H48=20.6	
	embryo	S,N,2	$ZnCJ_2$	-	-	28	-	10µM	E24=65.1 H24=4.0 E48=59.8 H48=6.3	
Asterias forbesi (starfish)	adult	S,M,2	$ZnCJ_2$	7.8	>4.0	20	20	1.5	LC0-168 hr	Eisler & Hennekey 1977
	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	2.6	LC50-168 hr	
	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	4.5	LC100-168 hr	
	-	S,M,2	-	-	-	-	-	1	LC0-168 hr	
	-	S,M,2	-	-	-	-	-	2.3	LC50-168 hr	
Clibanarius olivaceous (hermit crab)	larvae	NA	-	-	-	-	-	0.001-0.090	dose-dependent molting delays	Ajmalkhan 1986
Crassostrea cucullata (oyster)	3-d old larvae	S,N,2	-	-	-	-	-	0.05	GC50-96hr	Watling 1982
	13-d old larvae	S,N.2	-	-	-	-	-	0.85	GC50-96 hr	Watling 1982

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
	3-d old larvae	S,N,2: 4 days treatment, subsequent 4 days in control solution		-	-	-	-	0.13	GC50-8 days	
	13-d old larvae	S,N,2: 4 days treatment, subsequent 4 days in control solution	-	-	-	-	-	0.13	GC50-8 days	
Crassostrea gigas (Pacific oyster)	larvae	NA	-	-	-	-	-	0.010-0.020 (2*)	reduced larval settlement- 20 days	EPA 1987
	larvae	NA	-	-	-	-	-	0.07	abnormal shell development- 48 hr	EPA 1980
	larvae	NA	-	-	-	-	0.125	0.125	substrate attachment inhibited-5 days	EPA 1980 & 1987
	larvae	S,M,2	$ZnSO_4$	-	-	20-22	29	0.05	normal growth & development- 5 days	Brereton et al. 1973
fed	larvae	S,M,2	$ZnSO_4$	-	-	20-22	29	0.125	84% of eggs developed into larvae. (relative to control)	
fed	larvae	S,M,2	$ZnSO_4$	-	-	20-22	29	0.25	52% of eggs developed into larvae. (relative to control)	
fed	larvae	S,M,2	$ZnSO_4$	-	-	20-22	29	0.5	10% of eggs developed into larvae. (relative to control)	
fed	15-d old larvae	S,N,2	$ZnCl_2$	-	aerated solution	22-23	34	0.030-0.035 (4*)	EC50-6 days (# settling larvae)	Watling 1983
fed	35-d old	S,N,2	$ZnCl_2$	-	aerated solution	22-23	34	>0.050	GC50-11 days larvae	
fed	6-d old larvae 22-23	S,N,2	$ZnCl_2$	-	-	22-23	34	0.08	GC50-96 hr	Watling 1982

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
	34 0.08 GC50-96hr									
Oysters (fed)	10-d old larvae	S,N,2	$ZnCl_2$	-	-	22-23	34	0.095	GC50-96 hr	Watling 1982
	embryo	S,M,2	$ZnSO_4$	8.1	6.5-8.0	20	33.79	0.119	EC50-48 hr	Martin 1981
	~18months	F,N,2	-	-	-	22	-	8	glycine transport rate significantly reduced (p=0.05-0.01)	Lin et al. 1992
C. margaritacea (oyster) (fed)	3-d old larvae	S,N,2	$ZnCl_2$	-	aerated solution	22-23	34	0.045	GC50-96 hr	Watling 1982
(oyster) (fed)	13-d old larvae	S,N,2	$ZnCl_2$	-	aerated solution	22-23	34	0.085	GC50-96 hr	
Crassostrea margaritacea (oyster) (fed)	3-d old larvae	S,N,2: 4 days treatment, subsequent4 days in control solution	$ZnCl_2$	-	aerated solution	22-23	34	0.075	GC50-8days	
	13-d old larvae	same as above	$ZnCl_2$	-	aerated solution	22-23	34	0.12	GC50-8days	
Dendraster excentricus (sand dollar)	sperm	F,M,1	$ZnCl_2$	8.0-8.1	measured	12.5-13.0	30	0.028	1-h EC50 for sperm/fertilization	Dinnel et al. 1989
Haliotis rufescens (red abalone)	larvae	F,M,1	$ZnSO_4$	7.85-7.95	7.0-8.3	14.0-17.5	-	0.019 (3*)	NOEC-9 days (metamorphosis)	Hunt & Anderson 1989
	larvae	F,M,1	$ZnSO_4$	7.85-7.95	7.0-8.3	14.0-17.5	-	0.05	EC50-9 days (metamorphosis)	
	larvae	F,M,1	$ZnSO_4$	7.85-7.95	7.0-8.3	14.0-17.5	-	0.068	EC50-48 hr (metamorphosis)	
	embryo	F,M,1	$ZnSO_4$	7.90-7.95	5.7-7.9	13.0-16.0	33-33	0.04	NOEC-48 hr (shell development)	
	embryo (incubated)	F,M,1	$ZnSO_4$	7.90-7.95	5.7-7.9	13.0-16.0	33-36	0.068	EC50-48 hr (shell development)	
	larvae	F,M,1	-	-	-	-	-	0.13	LC50-17 days	McLeese 1976

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
Homarus americanus (American lobster)	adult	F,M,1	-	-	-	-	-	13	LC50-11 days	
Ilyanassa obsolete (gastropod mollusk)	fertilized eggs (incubation)	F,N,2	zinc salt	-	-	20	-	10-7-10-6µM	no apparent effect	Conrad 1988
	fertilized eggs (incubation)	F,N,2	zinc salt	-	-	20	-	10-5 µM	abnormal veliger development	
	fertilized eggs (incubation)	F,N,2	zinc salt	-	-	20	-	10-4-10-3 µM	abnormal late cleavage	
	fertilized eggs (incubation)	F,N,2	zinc salt	-	-	20	-	10-2µM (1*)	stops 1st cleavage and normal cell shape changes	
Lytechinus variegatus (sea urchin)	sperm	S,N,2	$ZnSO_4$	-	25	-	-	0.068	EC50-1 hr (viability)	Nipper et al. 1993
	embryo	S,N,2	$ZnSO_4$	-	25	-	-	0.074	EC5-24 hr (development)	
Mya arenaria (softshell clam)	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	1	LC0-168 hr	Eisler & Hennekey 1977
	adult adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	3.1	LC50-168 hr	
	adult	S,N,2	$ZnCl_2$	7.8	>4.0	20	20	5	LC100-168 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	22	30	0.9	LCO-168 hr	Eisler 1977
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	22	30	1.55	LC50-168 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	22	30	3	LC100-168 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	17.5	30	1.5	LC0-504 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	17.5	30	2	LC50-504 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	17.5	30	2.5	LC100-504 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	17.5	30	1.75	LC0-336 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	17.5	30	2.65	LC50-336 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	17.5	30	3	LC100-36 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	17.5	30	10	LC0-168 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	17.5	30	>10.0	LC50-168 hr LC100-168 hr	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	4	30	25	LC0-168 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	4	30	>25.0	LC50-168 hr LC100-168 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	4	30	25	LC0-336 hr	
	adult	S,N,2	$ZnCl_2$	7.95	>4.0	4	30	>25.0	LC50-336 hr LC100-336 hr	
Mysidopsis bahia (crustacea: mysidacea) fed	24-h old post-larvae	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	<0.002 (control)	73% survival- 36 days	Lussier et al. 1985
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	0.059	90% survival- 36 days	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	0.12	80% survival- 36 days	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	0.231	* *40% survival- 36 days	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	0.454	*0% survival- 36 days	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	<0.002 (control)	21 days to first brood	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	0.059	22 days to first brood	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	0.12	21 days to first brood	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	0.231	*24 days to first brood	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	<0.002 (control)	0.71 young/female/reproductive day	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	0.059	0.47 young/female/reproductive day	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	0.12	0.81young/female/reproductive day	
	as above	F,M,1	$ZnCl_2$	7.8-8.2	-	21	30	0.231	*0.10 young/female/reproductive day	
Mytilus edulis (mussel)	adult	NA	-	-	-	-	-	0.06	EC50:2-6 days (shell growth)	EPA 1987
	adult	NA	-	-	-	-	-	1.8	reduced byssal thread production	
	embryo	NA	-	-	-	-	-	0.096-0.314	EC50-72 hr (development)	
	adult	NA	-	-	-	-	-	5	LC50-7 days	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
	embryo	S,M,2	$ZnSO_4$	8.1	6.5-8.0	17	33.79	0.175	EC50-48 hr *abnormally-shaped larvae)	Martin 1981
	3-4cm.	S,N,2, brackish water	$ZnCl_2$	-	-	-	-	0.64	EC50-24 h (byssogenesis) *observations made for 6 weeks after exposure	Hietanen et al. 1988
		S,N,2, brackish water	$ZnCl_2$	-	-	-	-	1.35	EC50-24 h (opening response) *observations made for 6 weeks after exposure	
	adult	S,N, 2, 24-h plus exposure plus 6 wk postexposure	-	-	-	-	-	20.8	EC50 (24-h exposure plus six weeks postexposure); none dead during postexposure	
	0.233 g	static, unfed	-	-	-	15.5	35	5	LC100-16 days	Amiard et al. 1986
	12-16 months	F,M,1	$ZnCl_2$	-	-	17.0 (av.)	33.1 (average)	25 50	Growth reduction significant: Day 2	Stromgren 1982
	12-16 months	F,M,1	$ZnCl_2$	-	-	17.0 (av.)	33.1 (average)		Growth reduction significant: Day 1	
	12-16months	F,M,1	$ZnCl_2$	-	-	17.0 (av.)	33.1 (average)	~60	EC50 (growth)	
	12-16months	F,M,1	$ZnCl_2$	-	-	17.0 (av.)	33.1 (average)	Š200	no visible change in behaviour	
	12-16 months	F,M,1	$ZnCl_2$	-	-	17.0 (av.)	33.1 (average)	>100	Growth stabilized at ~20% of control growth	
	sperm	NA	-	-	-	-	-	65.4	Respiration inhibited 50% - 20min.	Akberali et al. 1985
Nassarius obsoletus (snail)	adult	NA	-	-	-	-	-	0.2	decreased oxygen consumption-72 hr	EPA 1980
	egg	F,N,2	-	-	-	-	-	0.65	abnormal veliger development	Conrad 1988
	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	5	LC0-168 hr	Eisler & Hennekey 1977
	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	7.4	LC50-168 hr	
	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	30	LC100-168 hr	
Nereis diversicolor (sandworm)	adult	S,M,2	-	-	-	-	-	1.5	LC0-168 hr	
	adult	S,M,2	-	-	-	-	-	2.6	LC50-168 hr	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
Nereis virens (sandworm)	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	1.5	LC0-168 hr	
	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	2.6	LC50-168 hr	
	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	4.5	LC100-168 hr	
Palaemon elegans (prawn)	-	NA						0.562	LC67-21 days	Nugegoda & Rainbow 198
Pagarus longicarpus (crab)	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	0.1	LC0-168 hr	Eisler & Hennekey 1977
	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	0.2	LC50-168 hr	
	adult	S,M,2	$ZnCl_2$	7.8	>4.0	20	20	0.5	LC100-168 hr	
*Praunus flexuosus (*mysid)	-	S,N,2	-	-	-	5	4.5 ppt	2	LC50-192hr	McLusky & Hagennan 1987
Tisbe holuthuriae (copepod) fed Ulva	-	S,N,2	-	-	-	-	-	Ulva with 10mg/L	47% dead-7 d	Verriopoulos & Moraitou-Apostolopoulou 1980
	-	S,N,2	-	-	-	-	-	Ulva with 50mg/L	17% dead-2d 100% dead- 7d	
Uca annulipes (fiddler crab)	24-29 mm wide, from unpolluted water	S,M,2	-	-	-	29	20	12.93	oxygen consumption sig. ($p<0.01$) lower than control- 48 hr	Devi & Rao 1989
	as above	S,M,2	-	-	-	29	20	24.06	oxygen consumption sig. lower than control- 96 hr	
	as above	S,M,2	-	-	-	29	20	66.4	oxygen consumption sig. lower than control- 48 hr	
	as above	S,M,2	-	-	-	29	20	76.95	oxygen consumption sig. lower than control- 96 hr	
Uca annulipes (fiddler crab)	as above	S,M,2				29	20	19.4	oxygen consumption sig. lower than control- 48 hr	Devi & Rao 1989
	as above	S,M,2				29	20	20.65	oxygen consumption sig. lower than control- 96 hr	
	as above	S,M,2				29	20	66.42	oxygen consumption sig. lower than control- 48 hr	
	as above	S,M,2				29	20	74.35	oxygen consumption sig. lower than control- 96 hr	

KEY

LC = Lethal Concentration	M == Measured
EC = Effective Concentration	N =Nominal
S = Static Test Method	NA= Not Available
F == Flowthrough Test Method	1 = Primary 2 = Secondary
NOEC = No Observed Effect Concentration	MEC = Minimum Effect Concentration
GC = Reduction in Growth	
E == Emerging, H == Hatching	**Example: E24=8.7 means 8.7% emerged in 24-h

Table 5. Toxicity of zinc to marine algae and macrophytes

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
Fucus vesiculosus (Marine macroalgae)	-	NA	-	-	-	-	-	3.5	no adverse effects	EPA 1987
	-	NA	-	-	-	-	-	7	growth retardation	
Glenodium halli (Dinoflagellate)	-	NA	-	-	-	-	-	0.02 (3*)	chlorophyll reduced 65%- 2 d	
Gymnodium splendens (Dinoflagellate)	-	NA	-	-	-	16-30	-	0.110-0.392	chlorophyll reduced 65%- 2 d	
Laminaria digitata (Kelp)	-	NA	-	-	-	-	-	0.1	growth inhibition- 24 days	
Marine algae (4 species)	-	NA	-	-	-	-	-	0.05-0.50	decrease in cell numbers	
Marine algae (5 species)	-	NA	-	-	-	-	-	0.1	growth inhibition-48 hr	
Marine macroalgae (4 species)	-	NA	-	-	-	-	-	0.1	no adverse effects	
	-	NA	-	-	-	-	-	1.4	growth reduction	
Nitzchia Closterium (Diatom)	log-phase growth stage	S,N,2	-	-	-	21	-	0.065	IC50-4 days (cell division)	Stauber & Florence 1990
Phaeodactylum tricornutum (Diatom)	-	S,N,2	$ZnSO_4$	-	-	13	-	0	Division rate 100% of control culture	Bræk et al. 1980
	-	S,N,2	$ZnSO_4$	-	-	13	-	0.5	88% of control culture	
	-	S,N,2	$ZnSO_4$	-	-	13	-	1	89% of control culture	
	-	S,N,2	$ZnSO_4$	-	-	13	-	2	85% of control culture	
	-	S,N,2	$ZnSO_4$	-	-	13	-	3	81% of control culture	
Rhizosolenia sp. (Marine algae)	-	F,M,1	-	-	-	-	-	0.015--0.025 (4*)	photosynthesis reduction	Davies and Sleep 1979; Spear 1981
Schroederella schroederi (Diatom)	-	NA	-	-	-	-	-	0.019 (1*)	50% growth reduction- 48- 96h	EPA 1987
Skeletonema costatum (Diatom)	-	NA	-	-	-	-	-	0.0196 (2*)	adverse effects	Vymazal 1986

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
Skeletonema costatum (Clone Skel-O)	-	NA	-			-		0.05-0.1	20-23% growth reduction- 10-15 days	EPA 1987
	-	NA	-			-		0.265	metabolic disruption - 3 days	
	-	S,N,2	$ZnSO_4$			13		0	Division rate 100% of control culture	Bræk et al. 1980
	-	S,N,2	$ZnSO_4$			13		0.05	100% of control culture	
	-	S,N,2	$ZnSO_4$			13		0.1	100% of control culture	
	-	S,N,2	$ZnSO_4$			13		0.2	90% of control culture	
	-	S,N,2	$ZnSO_4$			13		0.4	82% of control culture	
Skeletonema costatum (Clone Skel-5)	-	S,N,2	$ZnSO_4$			13		0	Division rate100% of control culture	
	-	S,N,2	$ZnSO_4$			13		0.05	100% of control culture	
	-	S,N,2	$ZnSO_4$			13		0.1	80% of control culture	
	-	S,N,2	$ZnSO_4$			13		0.2	27% of control culture	
Thalassiosira pseudomona (Diatom)	-	S,N,2	$ZnSO_4$			13		0	Division rate 100% of control culture	
	-	S,N,2	$ZnSO_4$			13		0.1	100% of control culture	
	-	S,N,2	$ZnSO_4$			13		0.2	96% of control culture	
		NA								
		NA				-		0.5	41% growth reduction - 11 - 15 days	EPA 1987
		NA				-		0.823	50% growth reduction- 72 h	

KEY

IC = Inhibition Concentration	M=Measured
S = Static Test Method	N=Nominal
F = Flowthrough Test Method	NA= Not Available
	1 =Primary
	2 = Secondary

Table 6. Effect of zinc on agricultural crops and soil organisms.

Organism/Species	***Effect concentration/or Zn (dry weight basis)***	***Effect/comments***	***Test conditions***	***Reference***
Crop/Plant				
Maize (*Zea mays*)	0.6 mg/kg soil; 20 mg/kg tissue	critical concentrations below which Zn will be deficient.	Pot and plot trials.	Liu et al., 1993
Barley cv. Gerbel (*Hordeum vulgare*)	26.2 mg/L (or 400 µM)	Concentration inhibited seedling growth.	Solution culture	Brune et al., 1995
Barley (*Hordeum vulgare*)	13.06 mg/L (or 200 µM)	Apoplastic protein content increased 3-fold as Zn conc. increased from 0.02 to about 200 µM	Hydroponic culture	Brune et al., 1994
Blackgram (*Vigna mungo*)	150 - 200 mg/kg soil	Macro & micro elements, Ca:Zn ratio decreased in leaves	Greenhouse expt.; soil pH 6.2; $ZnSO_4$	Kalyanaraman & Sivagurunathan, 1994
Blackgram cv. ADT4 (*V. mungo*)	155 mg/kg soil (total); 24 mg/kg soil (DTPA); 106 mg/kg (roots); 144mg/kg (leaves)	Threshold concentrations for 10% decrease in yield.	Greenhouse expt.; soil pH 6.2; $ZnSO_4$	Kalyanaraman & Sivagurunathan, 1993
Wheat (*Triticum aestivum*)	1.24 mg/L (or 19 µM) - roots; 3.14mg/L (or 48 µM) - tops	Root yield of Al-tolerant species decreased by 50%.	Solution culture	Wheeler et al., 1993
Wheat (*T. aestivum*)	1.83 mg/L (or 28 µM) - roots; 3.47 mg/L (or 53 µM) - tops	Root yield of Al-sensitive species decreased by 50%.	Solution culture	Wheeler et al., 1993
Sweet potato (*Ipomoea batatas*)	10 mg/kg tissue (deficiency); 90 - 300 mg/kg tissue (toxicity)	Critical concentrations in the leaf blade; solution Zn conc. not given.	Solution culture; pH 5.5 - 6.0	O'Sullivan et al., 1993
Maize cv. Vijay (*Z. mays*)	50 mg/kg soil (extractant unknown)	Reducing, non-reducing & total sugar contents decreased from 10.5 to 8.6%	Pot culture; sandy soil	Narwal & Singh, 1993
Winter wheat cv. 311303 (*T. aestivum*)	0.5 mg/L	Small chloroplasts, fewer grana & stroma lamellae, some swollen lamellae, and increase in osmiophilic globules & mitochondria near the chloroplast.	Solution culture	Wang et al., 1993
Spring wheat cv. Eta (*T. aestivum*)	1,000 mg/kg soil; 300mg/kg soil (safe level)	Reduced crop yield; 300 mg/kg prevents phytotoxicity and excessive accumulation of Zn in plants to protect	Pot expts.; sandy soil; soil pH 6.6 (in KCl); $ZnSO_4$	Dudka et al., 1994
Radish (*Raphanus sativus*)	343 mg/kg soil; 86-162 mg/kg tissue	Toxic threshold in soil for yield reduction; and tissue conc. causing 50% reduction in yield	Pot (soil+mine waste); pH 7.1-7.6: sicl & loam	Davies, 1993
Radish (*R. sativus*)	36.1 mg/kg tissue to 1013 mg/kg hypocotyls	Reduced yield by 50%.	solution cultures	Davies, 1993
Beans (*Phaseolus vulgaris*)	200mg/L	Enzymatic activities and ethylene production increased	Solution culture	Weckx et al., 1993

Organism/Species	Effect concentration/or Zn (dry weight basis)	Effect/comments	Test conditions	Reference
American ginseng (*Panx quinquefolis*)	0.05 mg/L (deficiency); 0.3 mg/L (optimum)·0.5 mg/L (toxic)	Critical concentrations for deficiency, optimum growth and toxic conditions.	Solution culture	Ren et al., 1993
Carrot; Root beet; Onion; Lettuce; Swedes	106 mg/kg soil (CH_3COOH extracted); 424 mg/kg soil (total-estimated)	Sludge treatment reduced yield; 4-times the quantity of Zn is required to cause similar reduction in yield at pH 7.0.	Field plots; soil pH 6.2; loamy sand	Williams, 1980
Peas (*Pisum sativum L.*) Oats (*Avena sativa L.*)	66 - 132 mg/kg sand; 2016 mg/kg dry matter	Growth & dry matter yield severely reduced (data on yield & growth not given).	Sand/nutrient solution culture: pH 5.8-6.6	Lyszcz & Ruszkowska, 1992
Barley (*H. vulgare*); Ryegrass (*L. perenne*)	120-520 (median= 210) mg/kg tissue (Barley); 221 mg/kg tissue (ryegrass)	Critical concentration for toxic reactions.	Sand/nutrient solution culture	Davis and Beckett, 1978
Pearl millet (*Pennisetum glaucum*)	196 mg/L(0.003 M) to 327 mg/L (0.005 M)	Critical levels for toxic reaction; significant reduction in growth.	Nutrient soln; $ZnSO_4$	Davis et al., 1993
Soil organisms/Invertebrates				
Nematodes (*Caenorhabditis elegans*)	255 mg/kg (Worsham sl, pH 5.1); 360 mg/kg (Cecil sl, pH 6.2); 392mg/kg (Devidson l, pH 6.1); 549 mg/kg (Dyke cl, pH 6.2)	Average LC50 concentrations in soils; Worsham (16% c, 3% O.M.), Cecil (16% c, 1.7% O.M.), Davidson (20% c, 3.4% O.M.), Dyke (39% c, 2.2% O.M.)	Petri dishes in laboratory	Donkin & Dusenbery, 1994
Earthworm (*Eisenia fetida*)	662 mg/kg - soil (total; pH 6.3)	Average 14-d LC50 in artificial soil (20% kaolin clay, 10% O.M.	Laboratory	Neuhauser et al., 1985
Earthworm (*Eisenia fetida*)	1010 mg/kg soil (14-d LC50); 745 mg/kg soil (56-d LC50); 289 mg/kg soil (56-d NOEC-M); 276mg/kg soil (56-d EC50- CP); 199 mg/kg soil (56-d NOEC-CP)	Effect (LC50 & EC50) and no effect (NOEC) total concentrations in the artificial soil for mortality (M) and cocoon production (CP)	Laboratory	Spurgeon et al., 1994
Rhizobium leguminosarum biovar trifolii.	200 mg/kg soil (pH 5.6 - 6.4)	Concentrations in soil (silty loam) causing decrease in rhizobial numbers	Field experiments	Chaudri et al., 1993
Microbial biomass production	375 mg/kg soil (total); 142mg/kg soil ($CaCl_2$ extradct)	Threshold for decrease in biomass (sandy loam with average pH 6.5.	Field experiments	Chander & Brookes, 1993
Microbial biomass production	600 mg/kg soil (total); 15 mg/kg soil (water soluble)	46% decrease in biomass (loam with average pH 6.1)	Laboratory	Leita et al., 1995
Accumulation in Plants				
Spring wheat cv. Eta (*T. aestivum*)	AI= 0.2-0.45 (grain); AI = 0.9-1.6 (straw) (Soil Zn levels ranged from 42 – 1500 mg/kg)	Accumulation index (AI) is the ratio between Zn in treated plants and in soils.	Pot expts. in sandy soil	Dudka et al., 1994
Groundnuts cv.	>240 mg/kg in shoots	Toxicity symptoms occurred when Zn	Pot culture in sandy clay	Davis & Parker, 1993

Organism/Species	***Effect concentration/or Zn (dry weight basis)***	***Effect/comments***	***Test conditions***	***Reference***
Florunner (*Arachis hypogaea*)		in plants shoot > 240 mg/kg & Ca:Zn ratios < 35.	loam & sandy clay	
Red beet cv. Crimson Globe	90-1 100 mg/kg leaf; 250mg/kg soil (total)	Threshold concentration for yield reduction.	Pot culture; soil pH 6.5; sandy loam	Sanders et al., 1987
White.clover cv. Grasslands Huia	400 - 500 mg/kg leaf; 250mg/kg soil (total)	Threshold concentration for yield reduction.	Pot culture; soil pH 6.5; sandy loam	Sanders et al., 1987
Perennial ryegrass (*Lolium perenne*)	319 mg/kg soil (total); 140mg/kg leaf	Plant yield decreased sharply above these concentrations.	Pot culture; soil pH 7; sandy loam	Davis & Carlton-Smith, 1984
Perennial ryegrass cv. Melle (*Lolium perenne*)	210 mg/kg soil@ pH= 5.0-5.5; 246mg/kg soil @ pH= 5.5-6.0; 300 mg/kg soil @ pH = 6.0-7.0; 591 mg/kg soil@ pH> 7.0;	Maximum permissible concentrations based on proportional changes in ryegrass grown under different pH conditions.	Field experiments	Smith, 1994
Lettuce cv. Climax (*Latuca sativa L.*)	500 mg/kg tissue; 0.33 mg/L (5µM) to 2.15 mg/L (33µM)	Threshold for phytotoxicity in tissue & solution.	Solution culture; pH 6.2	Berry and Wallace, 1989
Petunia (*Petunia hybrida*)	16 mg/L in nutrient solution	Leaf yellowing symptoms developed at and above this concentration.	Pot culture (peat material	Lee et al.,1992
Bush beans cv. Contender (*P. vulgaris L.*)	95 mg/kg mature leaves; 134 mg/kg new leaves; 242 mg/kg stems; & 486 mg/kg roots	Phytotoxic threshold concentrations (for 10% growth reduction)	Solution culture; pH 5; $ZnSO_4.7H_2O$	Ruano et al., 1987
Bush beans (*P. vulgaris L.*)	0.88 mg/L (or 13.5 µM Zn)	23% reduction in net assimilation rate & up to 50% decrease in root growth	Solution culture; pH 5; $ZnSO_4.7H_2O$	Ruano et al., 1988
Dwarf beans (*P. vulgaris L.*)	226 mg/kg leaves	Phytotoxic threshold concentrations	Solution culture; pH 5; $ZnSO_4.7H_2O$	Van Assche et al., 1988
Paddy cv. Pusa-33 (*Oryza sativa L.*)	190 mg/kg plant; 26 mg/kg soil (EDTA); 12 mg/g soil (DTPA); 41 mg/kg soil (total)	Critical limits for 50% reduction in yield.	Pot culture; $ZnSO_4$	Rattan & Shukla, 1984
Wheat	7 mg/kg soil (DTPA) or 25 mg/kg soil (total); 100 mg/kg soil (total)	Yield decreased above these conc. (NOEC); Yield decreased (LOEC)	Pot culture; loamy sand; $ZnSO_4$	Takkar & Mann, 1978
Maize	11 mg/kg soil (DTPA) or 50 mg/kg soil (total); 100 mg/kg soil (total)	Yield decreased above these conc. (NOEC); Yield decreased (LOEC)	Pot culture; loamy sand; $ZnSO_4$	Takkar & Mann, 1978
Peanuts (*Arachis hypogaea L.*)		Plant Zn level determined by soil pH.	Field; loamy sand; soil pH 5.5 - 6.9	Parker et al., 1990

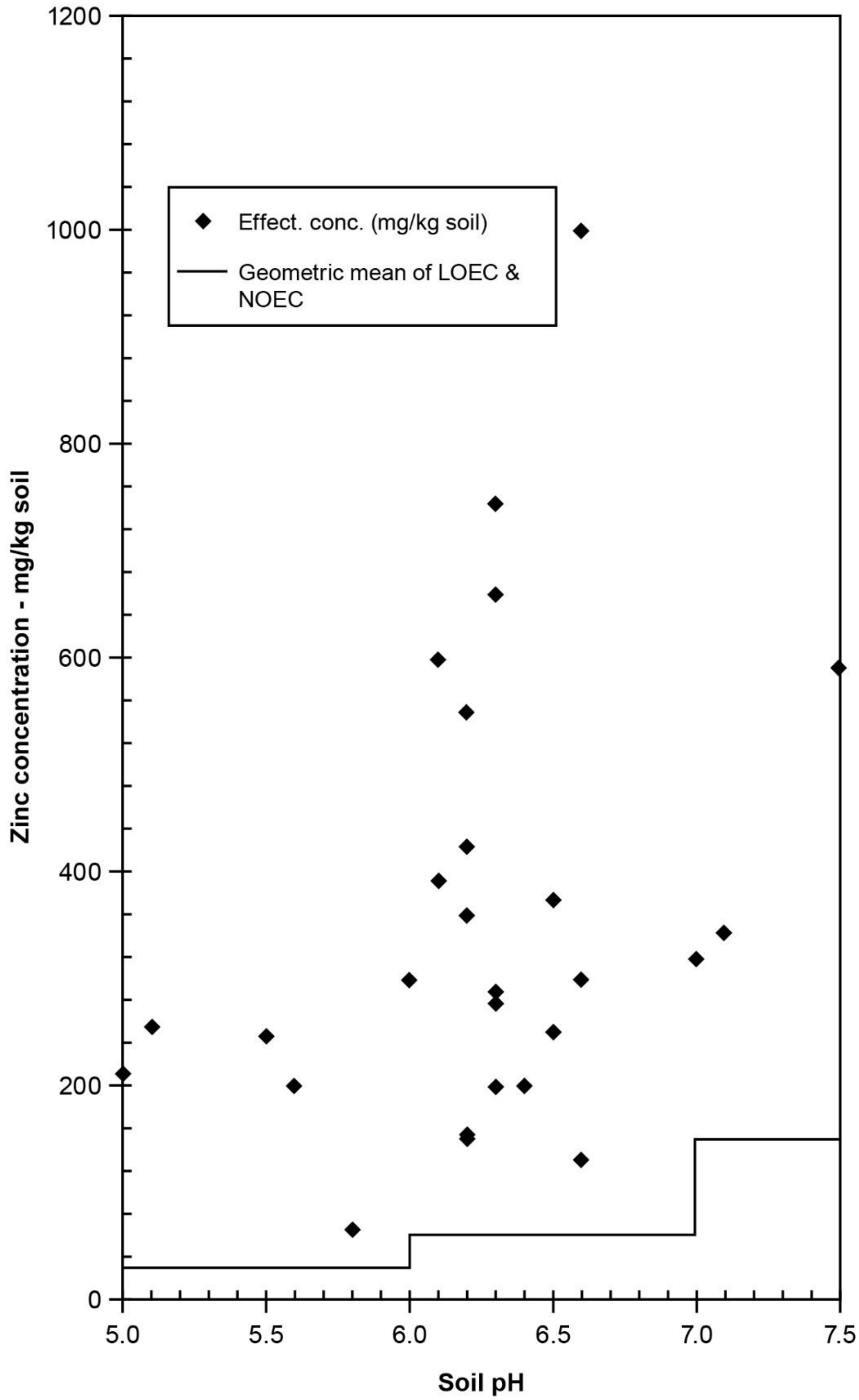

Figure 1. Zinc toxicity and geometric mean of lowest and no observed effect level