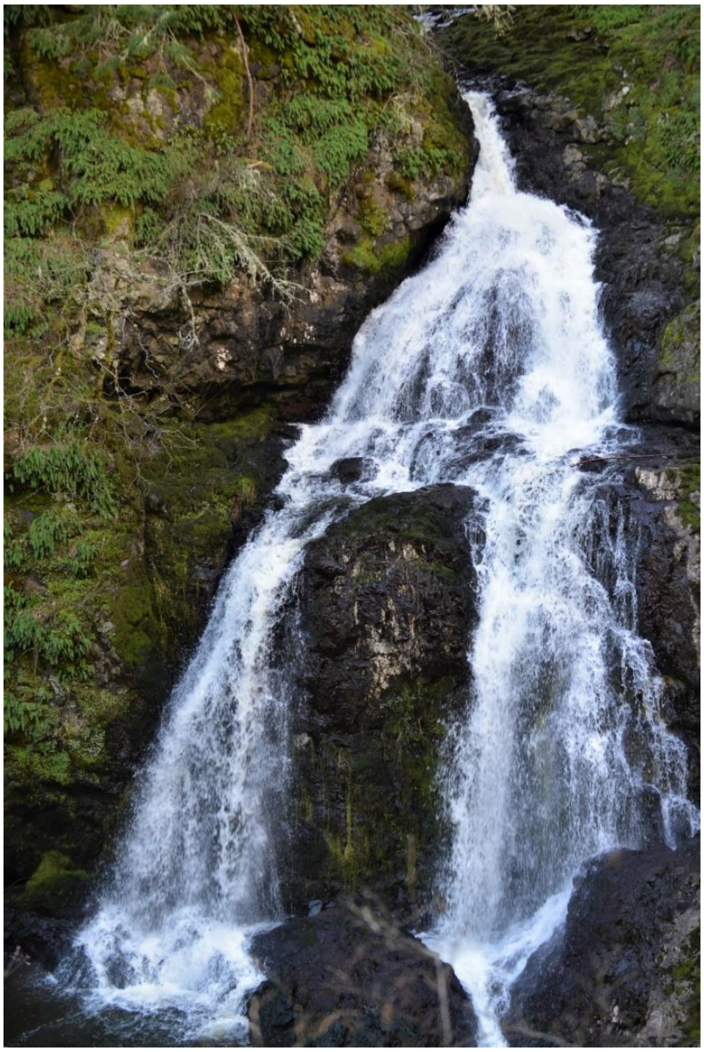
WATER QUALITY GUIDELINE SERIES

Zinc Water Quality Guidelines (Reformatted Guideline from 1997)

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



No. WQG-19

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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Notes on Reformatted Version:
Sections of this report on industrial water use, drinking water and recreation have been removed. B.C. adopts Health Canada drinking water and recreation guidelines and 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 1). 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 freshwater and marine aquatic life and agricultural water (irrigation and livestock watering) uses.

Table 1. Recommended guidelines for Zinc

Water use	Guideline (µg: Total Zn/L)
Freshwater Aquatic Life *	
• ***Maximum Concentration +***	***33 + 0.75 (water hardness-90)***
<u>Water hardness</u>	or
≤90 mg/L $CaCO_3$	33
100 mg/L $CaCO_3$	40
200 mg/L $CaCO_3$	115
300 mg/L $CaCO_3$	190
400 mg/L $CaCO_3$	265
• ***30-d Average Concentration ++***	***7.5 + 0.75 (water hardness-90)***
Water hardness	or
≤90 mg/L $CaCO_3$	7.5
100 mg/L $CaCO_3$	15
200 mg/L $CaCO_3$	90
300 mg/L $CaCO_3$	165
400 mg/L $CaCO_3$	240
Marine Life	10
Irrigation	
Soil pH < 6	1000
Soil pH 6 - < 7	2000
Soil pH ≥ 7	5000
Livestock Watering	2000

* When ambient zinc concentration in the environment exceeds the guideline, then further degradation of the ambient or existing water quality should be avoided ;
+ Instantaneous maximums;
++ Average of five weekly measurements taken over a 30-day period.

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

Zinc is most toxic to microscopic organisms in the aquatic environments. It is also an essential element for aquatic and terrestrial biota and its removal from the environment below certain levels can also be harmful due to its deficiency. Zinc guidelines, tabulated above, are summarized in the chapter on Recommended Criteria. A more detailed discussion of the guidelines or criteria is presented in the main body of the report.

Zinc may bind to particulate matter. Soluble species of zinc are readily available for biological reactions and, therefore, considered as most toxic. It has been shown that zinc in water is a better predictor of fish tissue contamination than zinc in either sediment or invertebrates (i.e., food source). It is, therefore, recommended that the zinc guideline may be interpreted in terms of the dissolved metal fraction when

the total zinc concentration in the environment exceeds the guideline due to particulate matter and adverse effects due to zinc are not obvious.

PREFACE

The Ministry of Environment, Lands and Parks develops ambient water quality guidelines for British Columbia. This work has two goals:

- to provide guidance for the evaluation of data on water, sediment and biota, and
- to provide basis for setting site-specific ambient water quality objectives.

The guidelines represent safe conditions or safe levels of a substance in water. It is defined as “a maximum and/or a minimum value for a physical, chemical or biological characteristic of water, sediment or biota, which should not be exceeded to prevent detrimental effects from occurring to a water use under given environmental conditions.”

The guidelines are applied province-wide, but they are use-specific, and are being developed for these water uses:

- aquatic life and wildlife
- agriculture (livestock watering and irrigation)

The guidelines are established after considering the scientific literature, existing guidelines from other jurisdictions and environmental conditions in British Columbia. The scientific literature provides information about the effects of toxicants on various life forms. This information is not always conclusive because it is usually based on laboratory work that, at best, only approximates field conditions. To compensate for this uncertainty, and applying the “precautionary principle”, the criteria have built-in safety factors that are conservative, but reflect the natural background in the province.

The guidelines are used to set ambient site-specific water quality objectives for specific waterbodies. In setting the objectives, considerations are also given to present and future water uses, waste discharges, hydrology, limnology, oceanography, and existing background water quality.

In most cases, the objectives are the same as the guidelines. However, when natural background levels exceed the guidelines, the objectives could be less stringent than the guidelines. In rare instances-for example, if the resource is unusually valuable or of special provincial significance-the safety factor could be increased enabling objectives to be more stringent than the guidelines. Another approach would be to develop site-specific objectives by conducting toxicity experiments in the field. However, because this approach is costly and time consuming, it is seldom used.

Neither the guidelines nor the objectives derived from them have any legal standing. However, objectives can be used to calculate waste discharge limits for contaminants. These limits are outlined in waste management permits, orders and approvals, all of which have legal standing. Objectives are not usually incorporated as conditions of a permit.

Water quality guidelines or criteria are subject to review and revision as new information becomes available or as other circumstances dictate.

INTRODUCTION

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 zinc.

Zinc toxicosis is not a common problem, but zinc poisoning in humans (e.g., from acid foods or beverages stored in galvanized containers) and animals (e.g., from ingesting or exposure to galvanized metal objects, certain paints and fertilizers, zinc-containing coins, etc.) have been documented. Several factors such as water hardness, salinity, temperature, and the presence of other contaminants influence zinc toxicity in aquatic environments. This modification in zinc toxicity is the result of an effect on zinc availability and on sorption or binding of available zinc to biological tissues. The effect of water hardness on zinc toxicity is by far the most studied factor.

Clinical manifestations of zinc deficiency in animals include growth retardation, testicular atrophy, skin changes, and poor appetite. 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 humans, animals, birds, and plants have been reported in the literature.

Zinc ranks fourth among metals of the world in annual consumption, behind iron, aluminum and copper. British Columbia, Ontario, Yukon, and Northwest Territories are the major producers of zinc in Canada. Zinc uses are many:

- as a rust-resistant coating for iron and steel products;
- in the manufacture of brass and bronze in the die-casting industry;
- as ingredients of many household items, including utensils, cosmetics, powders, ointments, antiseptics and astringents, paints, varnishes, linoleum, rubber, and others;
- in the manufacture of parchment papers, glass, automobiles tires, television screens, dry cell batteries, electrical apparatus, agricultural fertilizers, insecticides, hardeners in cement and concrete, in printing and dyeing of textiles, in production of adhesives, as a flux in metallurgical operations, and as wood preservatives;
- in the manufacture of smoke bombs used for crowd dispersal, fire fighting exercises, and by military for screening purposes; and
- as medicine in the treatment of zinc deficiency, various skin diseases, wound healing, and to reduce pain in sickle cell anaemia patients.

The concentration of zinc 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 zinc deposits.

Historical zinc concentrations should be viewed with caution. Results from cleaner laboratory analytical methods with lower detection limits show that background zinc concentrations are lower than previously thought. Older high values may be the artifacts of high detection limits and artificial contamination during measurement.

RECOMMENDED CRITERIA

1. Aquatic Life

Freshwater: Chronic

To protect freshwater aquatic life from chronic effects, the average[1]3 concentration of total zinc (µg/L) should not exceed 7.5 µg/L when water hardness is ≤ 90 mg/L $CaCO_3$. When water hardness exceeds 90 mg/L $CaCO_3$, the average concentration is determined by the following relationship:

Average Concentration (µg/L) = 7.5 + 0.75 (Water Hardness in mg/L $CaCO_3$ – 90)

The recommended guideline at hardness values ≤ 90 mg/L $CaCO_3$ is based on the lowest observed effect level (LOEL) of 15 µg Zn/L for copepod and a safety factor of 0.5. The safety factor was based on the ratio of the no effect levels and LOELs found in the literature. The linearity between zinc toxicity and water hardness was assumed for practical reasons. The slope in the above equation was obtained from the two LOELs at 90 (15 µg Zn/L) and 200 mg/L $CaCO_3$ (180 µg Zn/L) after applying a safety factor of 0.5.

Freshwater: Acute

To protect freshwater aquatic life from acute and lethal effects, the maximum concentration of total zinc (µg/L) at any time should not exceed 33 µg/L when water hardness is ≤ 90 mg/L $CaCO_3$. When water hardness exceeds 90 mg/L $CaCO_3$, the maximum concentration is determined by the following relationship:

Maximum Concentration (µg/L) = 33 + 0.75 (Water Hardness in mg/L $CaCO_3$ – 90)

The guidelines for maximum concentration are based on 96-h LC_{50} of 66 µg/L at 9.5 mg/L $CaCO_3$ for rainbow trout The slope and the start of the relationship between zinc toxicity and water hardness was assumed to be the same as that for the chronic toxicity.

Acute LOELs lower than 66 µg/L were reported in literature. However, they were not used in development of the guidelines, because the data were dated, original articles were not available for confirmation of data quality, or data were incomplete (e.g., water hardness was not stated). Such rejection of suspect or incomplete data is consistent with the CCME and the Ministry of Environment, Lands and Parks protocols for the development of guidelines.

Marine water: Chronic

To protect marine aquatic life in marine environments, the average [4] concentration of total zinc should not exceed 10 µg/L.

The recommended guideline is based on lowest observed effect (chronic) levels of 19-19.6 µg/L zinc for the marine alga *S. schroederi* and *S. constatum.* A safety factor of 0.5 was used.

Marine water: Acute

To protect aquatic life from acute or lethal effects in the marine environment, the maximum concentration of total zinc at any time should not exceed 55 µg/L.

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[1] Arithmetic mean is computed from five weekly samples collected over a 30-day period.

The recommended guideline is based on lowest observed acute values of 112-168 µg/L (96-h LC_{50}) for Arctic grayling and 119-310 µg/L (48-h LC_{50}) for Pacific oyster. A safety factor of 0.5 was used.

2. Irrigation

The maximum concentration of total zinc in irrigation water supplies should not exceed 1 000 µg/L for soils with pH <6.0, 2 000 µg/L for soils with pH ranging between 6.0 and 7.0, and **5** 000 µg/L for soils with pH 7.0.

These guidelines replace the 1987 CCME guidelines which were based on old (pre 1980) data.

3. Livestock Watering

To protect livestock water use, the concentration of total zinc in livestock watering should not exceed 2 000 µg/L.

This guideline replaces the 1987 CCME guideline which was based on old (pre 1980) data.

APPLICATION OF CRITERIA FOR AQUATIC LIFE

Zinc is a ubiquitous in the environment. Its impact on the environment depends upon several factors related to Zn sources and environmental variability. Therefore, care must be exercised when the water quality guidelines are applied to assess environmental impacts of zinc.

1. Assessment of Existing Water Quality

Zinc shows variable behaviour in binding to particulate matter depending upon physical-chemical characteristics of the aquatic system. The literature shows that particulate zinc in rivers and lakes varied from 10-78% of the total zinc concentration. Furthermore, soluble species of zinc are readily available for biological reactions and, therefore, most toxic. It has also been shown in the literature that zinc concentration in water is a better predictor of fish tissue contamination than the concentration in either sediment or invertebrates (i.e., food). In view of these facts, it is recommended that the zinc guideline should be interpreted in terms of the dissolved metal fraction when the total zinc concentration in the environment exceeds the guideline due to particulate matter and adverse effects due to zinc are not obvious.

The water quality guidelines recommended in this document are primarily based on controlled, laboratory bioassays in which the toxic effects on organisms were measured in terms of the zinc levels in water. However, the zinc body burden of aquatic organisms in their natural environments is the result of exposure to both water and food sources. Zinc associated with the sediment fraction may also become available to the organisms under favourable environmental conditions. Thus, the zinc concentrations in water alone should not be taken as a true reflection of the potential zinc problem in a given waterbody. Other assessment techniques may be required to address issues related to zinc, including measurement of zinc concentrations in fish and/or sediment and long-term bioassays with resident species using local water. If available, guidelines for maximum and average zinc concentrations in fish tissue and sediment should also be used to assess existing water quality. Long-term bioassays are complex and costly; they are likely to be undertaken for waterbodies with high resource values and which are threatened by a controllable point-source of zinc pollution.

2. Setting of Water Quality Objectives

In most cases, water quality objectives will be the same as the guidelines. When concentrations of zinc in undeveloped waterbodies are less than the recommended guidelines, then more stringent values, if justified, could apply. In some cases, socio-economic or other factors (e.g., higher background levels) may justify objectives which are less stringent than the guidelines. Site-specific impact studies would be required in such cases.

Zinc availability, and hence its toxicity, in the aquatic environment can be influenced by many factors, including water hardness. Although the literature alludes to this fact, there is a general lack of available research in this area. However, methods (e.g., water effects ratio, resident species toxicity in the field, etc.) are available to adapt the recommended guidelines to a given site by considering these factors (other than hardness which has been considered in this document). Where necessary, these methods can be employed to set site-specific water quality objectives. Because these approaches are costly and time consuming, they are seldom used.

In some instances, the ambient or existing concentrations of zinc in the environment may exceed the recommended guidelines. This may be true especially in the soft water (hardness ≤ 90 mg/L $CaCO_3$)

environments. To protect aquatic life in such environments, it is recommended that degradation of the existing water quality should be avoided.

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CONTENTS

1. SUMMARY

Recommended Canadian Water Quality Guideline for Zinc

Water use	Guideline (µg/L)	Status
Aquatic Life - Freshwater*	***7+0.755(hardness-90)***	Interim
	or	
Water hardness (mg/L as $CaCO_3$)		
≤90	7.0	
100	14.5	
200	90	
300	165	
400	241	
Marine Life	10	Interim
Wildlife	Not recommended	
Irrigation		Full
Soil pH		
<6	1000	
6 - <7	2000	
≥7	5000	
Livestock Watering	2000	Full

* When ambient zinc concentration in the environment exceeds the recommended guideline, then further degradation of the ambient or existing water quality should be avoided.

2. INTRODUCTION

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, 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 humans, animals, birds, and plants have been reported in the literature (Eisler 1993). Zinc toxicosis is not a common problem, but zinc poisoning in humans (e.g., from acid foods or beverages stored in galvanized containers) and 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.

3. AQUATIC LIFE

3.1 Freshwater Life

3.1.1 *Recommended Guideline*

The interim maximum concentration of zinc for the protection of freshwater aquatic life should not exceed 7 µg/L at water hardness ≤ 90 mg/L $CaCO_3$. When hardness exceeds 90 mg/L $CaCO_3$, the recommended maximum concentration is determined by the following relationship:

$$\text{Maximum Concentration } (\mu g\ Zn/L) = 7+0.755\ (\text{Water Hardness in mg/L } CaCO_3 - 90)$$

According to this relationship, the recommended guidelines are as follows:

Water Hardness (mg/L $CaCO_3$)	Recommended Guideline (µg Zn/L)
≤90	7.0
100	14.5
200	90
300	165
400	241

3.1.2 *Summary of Existing Guidelines*

The Canadian Council of the Ministers of the Environment (CCME, formerly CCREM 1987) has recommended a maximum water quality guideline of 30 µg Zn/L to protect freshwater aquatic life in Canada. This guideline was proposed on an interim basis in 1987.

The U.S. EPA (1986) expressed their freshwater criteria for the protection of aquatic life as 1-h average (acute criterion) and 4-d average (chronic criterion) concentrations of the total recoverable zinc (TRZ) (Current recommendations are to interpret these criteria in terms of the dissolved[1] metal concentrations instead of TRZ- U.S. EPA 1993). They recommended that the 1-hour and 4-d average concentrations should not exceed the numerical values given by the expressions $e^{[0.8473(\ln(\text{hardness}))+0.8604]}$ and $e^{[0.8473(\ln(\text{hardness}))+0.7614]}$, respectively, more than once every three years. For example, at hardness of 50, 100, and 200 mg/L $CaCO_3$ the recommended 1-h average concentration are 65, 120, and 210 µg Zn/L, respectively. The corresponding 4-d average criteria are 59, 110, and 190 mg Zn/L, respectively. The U.S. EPA (1987) also noted in its document that if striped bass was as sensitive as some data indicated, it would not be protected by this criterion.

The Ontario Ministry of the Environment (OMOE 1979) recommended a water quality objective of 30 µg Zn/L, at all levels of water hardness, to protect aquatic life in the province. In a recent draft document, OMOE (1991) suggested that the provincial water quality objective for zinc should be reduced from 30 µg Zn/L to 16 µg Zn/L to accommodate the sensitivity of invertebrates to zinc. Manitoba has recommended a maximum water quality guideline for surface waters of 47 µg Zn/L to protect the most sensitive use, whereas the Province of Quebec has adopted the U.S. EPA (1987) criteria. Aquatic life was assumed to require the highest quality of water. On the other hand, Alberta has recommended a maximum water quality guideline for sutface waters of 50 µg/L total zinc, to protect the most sensitive water use of aquatic life. The Guidelines for the Discharge of Treated Municipal Waste Water for the Northwest Territories recommend that an increase in zinc levels is not to exceed 10% of the original background levels to protect aquatic life.

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[1] Concentration in the filtrate obtained through a 0.45µm filter.

Michigan State employed a statistical approach to calculate an aquatic chronic value as a function of water hardness. The Michigan zinc standards are 14 µg Zn/Lat 10 mg $CaCO_3$/L hardness, 54 µg Zn/L at 50 mg $CaCO_3$/L hardness, and 98 µg Zn/L at 100 mg $CaCO_3$/L hardness (Zugger 1988).

The British Water Research Centre recommended an allowable zinc standard that increased with water hardness. The recommended levels were 8 µg Zn/Lat 10 mg CaCO/L, 50 µg Zn/Lat 50 mg CaCO/L, 75 µg Zn/Lat 100 mg $CaCO_3$/L, and 125 µg Zn/Lat 500 mg $CaCO_3$/L (Mance and Yates 1984).

The water quality criteria for European freshwater fish published by the European Inland Fisheries Advisory Commission (EIFAC 1973) was stated as follows: "pending the availability of more information it is tentatively suggested that for the maintenance of thriving populations of fish the annual 95-percentile of concentration of zinc should be no greater than 0.1 of the appropriate 7-d LC50 at 15°C; thus the criteria in terms of concentration of zinc would depend upon water hardness and type of fish. The maximum annual 95-percentile concentration recommended by EIFAC are as follows: 30,200,300, and 500 µg Zn/Lat hardness 10, 50, 100 and 500 mg/L $CaCO_3$/L, respectively, for the protection of salmonids. The corresponding 95- percentile concentration for coarse fish (except minnow) are 300, 700, 1 000, and 2 000 µg Zn/L, respectively.

3.1.3 *Rationale*

Cusimano and Brakke (1986) reported a 96-h LC50 (causing mortality in 50% of the population) of 97 µg Zn/L for small (1-6 g) steelhead trout (*Oncorhynchus mykiss*) at a pH of 5.7 and hardness of 9.2 mg/L $CaCO_3$. The U.S. EPA (1980) and Mayer and Ellersieck (1986) reported 96-h LC50s for cutthroat trout (*Oncorhynchus clarki*) ranging from 61-600 µg Zn/L. Buhl and Hamilton (1990) exposed rainbow trout (*O. mykiss)* to zinc concentrations and reported a 96-h LC50 of 169 (µg Zn/L). The U.S. EPA (1980, 1987) exposed striped bass (*Marone saxatilis*) larvae and rainbow trout (*O. mykiss*) fry to aquatic zinc concentrations and reported 96-h LC50 values between 100-119 µg Zn/L and 90-93 µg Zn/L, respectively. There data suggest that the rainbow trout fry is slightly more susceptible to zinc than the bass.

Using ≤ 24 hr old fathead minnows (*Pimephales promelas*), Schubauer-Berigan et al. (1993) reported 96-h LC50s of 780, 330 and 500 µg Zn/Lat pH 6-6.5, 7-7.5 and 8-8.5, respectively. The fathead minnow (*P. promelas*) appear to be more tolerant to zinc in slightly acidic waters (pH 6-6.5), but the pH and acute toxicity relationship was not clear-cut from the data.

In 30-days tests with larvae of flagfish (*Jordanella floridae*) exposed to zinc, Spehar (1976) found that the growth of the larvae was adversely affected at 85 µg Zn/L; also, no larvae survived at the test concentrations of ^{3}139 µg Zn/L. The U.S. EPA (1987) reported the maximum acceptable toxicant concentration (MATC) of 26-51 µg Zn/L for flagfish; the lower value in the MATC range indicates the highest concentration that produced no measurable effect on growth, survival, reproduction, and metabolism during chronic exposure whereas the higher value indicates the lowest concentration that produced a measurable effect (Eisler 1993).

Anadu et al. (1989) reported a 120-h LC50 of 170 µg Zn/L for rainbow trout (*0. mykiss*) in soft water (hardness= 33 mg/L $CaCO_3$). Bradley and Sprague (1985) found a similar level of toxicity for the juvenile trout (*0. mykiss,* 4.5-7.5 g): the 96 h- to 120 h-LC50s ranged from 88 and 190 µg Zn/Lin soft waters (hardness= 31.3 mg/L CaCO) of pH about 5.5 and 7. In an earlier study, Sinley et al. (1974) reported a 23% mortality in 21 months in the rainbow trout (2 g fingerlings through sexually mature 2-yr old fish) exposed to 2 200 µg Zn/L. The NOEC (no observable effects concentration) causing zero percent mortality over the 21-month period was 320 µg Zn/L. These results suggest that the trout in the Bradley and Sprague (1985) tests were more sensitive to zinc than those in the Sinley et al. (1974) study. This difference was attributed to the use of harder water (hardness= 333 mg/L $CaCO_3$) in the Sinley et al. tests and softer water (hardness= 31.3 mg/L $CaCO_3$) in the Bradley and Sprague tests. Perwak et al. (1980) and the U.S. EPA

(1980, 1987) also observed that the rainbow trout displayed an avoidance behaviour when exposed to concentrations as low as 5.6 and 10 µg/L of zinc. However, such data (e.g., avoidance) are not acceptable for the derivation of Canadian Water Quality Guidelines (CWQG) because their relevance to environmental consequences in an aquatic ecosystem can not be ascertained (CCME 1991).

In chronic tests with fathead minnows (*P. promelas*)*,* the U.S. EPA (1987) reported reduced growth in the juvenile fish exposed to 125 µg Zn/L for seven days. Also, in the adult minnows, a 65-83% reduction in fecundity was observed in a ten-month exposure to 180 µg Zn/L (U.S. EPA 1980, 1987).

Sayer et al. (1989) reported that 60% -95% of the brown trout (*Salmo trutta*) yolk-sac fry population died in 20-30 days when exposed to zinc concentrations ranging from 4.9 to 19.6 µg/L in soft (hardness not given) acid (pH= 4.5) waters. Also, 6%-21% of the fry developed abnormal vertebrae (reduction in the calcification of the centra). Sayer et al. also reported that the fish mortality displayed an inverse dose-dependency relationship (i.e., mortality decreased as zinc concentration increased). Obviously, zinc was not the only factor that contributed to the fish mortality. The authors concluded that the high mortality of the fry in their tests was probably the result of a joint effect of zinc and hydrogen ion (H^+) toxicity.

Affleck (1952) reported a 28-d LC54 of 10 µg/L for rainbow trout exposed to zinc. The usefulness of this data for derivation of the Canadian Water Quality Guideline (CWQG) was questioned for several reasons: (a) the fish were raised in a hatchery environment that employed "galvanised hatching houses and/or ponds". Although they were treated with aluminum paint, the galvanised hatching houses or ponds and galvanized-iron pipe of the hatchery water system were all sources of zinc, (b) the data on zinc concentrations in the hatching house or a circular pond water were not presented. However, it was stated that only some ponds had zinc levels ^{2} 10 µg Zn/L, whereas in most of the hatching houses or the circular ponds water the dissolved zinc concentration ranged between 20 and 40 µg/L.

Among freshwater invertebrates, the daphnids are among the most susceptible species to low levels of zinc in the environment. Attar and Maly (1982) reported 96-h LC50 of 67.9 µg Zn/L at hardness of 130 mg/L $CaCO_3$ for the juvenile water flea (*Daphnia magna*). The U.S. EPA (1987) reported 96-h LC50s of 253 µg Zn/L for *Daphnia pulex* and 241 µg Zn/L for pond snails (*Physa eterostropha*). In a more recent study, Schubauer-Berigan et al. (1993) reported 96-h LC50s for the amphipod *Hyalella azteca* of 1 200, 1 500 and 290 µg Zn/L at pH (in water) values of 6 to 6.5, 7 to 7.5 and 8 to 8.5, respectively. The *H. azteca* experiments were conducted in harder water (280-300 mg/L $CaCO_3$) which, in part (in addition to difference due to species' characteristics), may have been the reason for lower sensitivity of the organism (relative to *D. magna* above) to zinc. The increase in water hardness seemed to effect Zn toxicity to the freshwater invertebrates in the same manner as seen in the freshwater fish (see section on interaction and modifying factors).

The two lowest lethal concentrations reported in the literature were: 72-h LC50s of 5 to 14 µg Zn/L for water flea *D. magna* (U.S. EPA 1987), and 40 µg Zn/L for zooplankton *D. hyalina* (48-h LC50; Baudouin and Scoppa 1974). The acute concentration quoted in the U.S. EPA (1987) appears to be an outlier. The quality of this data could not be ascertained because the original source was not available; however, it was clear that this test was conducted in an unusually high temperature environment (30°C).

Farris et al. (1989) exposed adult Asiatic clam (*Corbicula sp.*) to zinc and reported that 34 µg Zn/L (30-d EC50) reduced shell growth and weight of the juveniles in 30 days. They also reported a significant reduction in the enzymatic (cellulase) activity of the clams exposed to 34 µg/L zinc for 10 days. Francis and Harrison (1988) reported tissue deterioration and death within 21 days for freshwater sponge (*Ephydatia fluviatilis*) exposed to 32 Zn µg/L. In a study ranked secondary, Winner (1981) reported that new-born water flea (*D. magna*) exposed to ^{3}100 µg Zn/L experienced a significant reduction in longevity. The water flea experiment was conducted in a hard water (130-160 mg/L $CaCO_3$). This may account for its relatively higher tolerance to zinc as compared to the Asiatic clam (hardness= 66-88 mg/L $CaCO_3$) and the sponge (hardness = 30 mg/Las $CaCO_3$). A 10-d LC50 of 36.8 µg Zn/L (hardness= 36.8 mg/L $CaCO_3$) for the insect *Tanytarsus dissimilis* and a 70-d LC50 of 60 µg Zn/L (hardness= 15 mg/L $CaCO_3$) for the juvenile leech (*Erpobdella octulata*) were reported by Anderson et al. (1980) and Willis (1989), respectively.

Wong (1993), Clements et al. (1988), Marshall et al. (1983), and Mills (1976) produced some of the most sensitive effects of zinc on freshwater invertebrates. Wong (1993) reported LT50s (time affecting 50% of the organisms for longevity) of 9.8 and 10 days, respectively, for the crustacean *Moina macrocopa* exposed to 10 and 20 µg/L zinc. Wong also reported that a significant reduction in LT50 (4.25 days as compared to about 10 days in the control) occurred only when the crustaceans were exposed to 500 µg/L zinc. Clements et al. (1988) found that the abundance of macro invertebrates communities was significantly affected when exposed to 15 µg/L zinc in a natural stream environment. However, in their study, the macro invertebrates' communities were exposed to a metal mixture (15 µg Zn/L + 12 µg Cu/L) rather than zinc alone. Note that the copper concentration (12 µg/L) in the mixture exceeded the CCREM (1987) guideline for the protection of aquatic life and may have influenced the results of Clements and his co-workers. In field tests conducted with the lake zooplankton population and water placed in submerged carboys, Marshall et al. (1983) exposed 6 cladocera, 10 copepods, and 20 rotifers of Lake Michigan to 15 to 90 µg/L of zinc. Only one species of the cladocera, 4 of the copepods, and 4 of the rotifers were very sensitive and showed significant reduction in population at 15 µg/L zinc. The overall population of copepods was reduced by about 24% at 15 µg Zn/L, but no significant reductions in the overall population of rotifers and cladocera were observed until they were exposed to 30 µg Zn/L and 60 µg Zn/L, respectively. Mills (1976) found that the mean (over the 14-day exposure period) population growth of protozoa *Euglena gracilis,* exposed to zinc in water (zero to 750 µg/L) was inhibited significantly by the 7.5 µg Zn/L treatment. Mills' results were somewhat suspect because experimental conditions (viz., temperature) changed during the test; also, the cell population at the end of the experimental period was higher for the 75 and 750 µg Zn/L treatments than the 7.5 µg Zn/L treatment.

Starodub et al. (1987) recorded a 4-h EC50 (photosynthesis) of 250 µg/L for *S. quadricauda* exposed to zinc. In primary ranked tests, Mchardy and George (1990) reported that the green algae *C. glomerata* experienced the first toxic signs when exposed to 400 µg Zn/L; 2 of 4 samples showed cytoplasmic abnormalities. In 2 of 4 samples of the green algae, 99% of the filaments were completely colourless and dead when exposed to 4 000 µg Zn/L under the same test conditions. The U.S. EPA (1980) reported a 95% growth inhibition in 14 days in the unicellular green algae (*S. capricornutum*) exposed to 40-68 µg/L zinc. According to Bartlett et al. (1974), the rate of growth began to decline when the alga *S. capricornutum* was exposed to 30 µg Zn/L for two days; the algal growth rate was completely inhibited on exposure to 120 µg Zn/L. Huebert and Shay (1992) noted a decrease in multiplication rate when *L. trisulca* was exposed to a concentration greater than 195 µg Zn/L; the EC50 for the final yield was 325 µg Zn/L.

In more recent studies, Dirilgen and Inel (1994b) reported an IC50 (causing a 50% reduction of frond growth as compared to the control) of 10 000 µg Zn/L for *Lemna minor.* In terms of relative growth, the rate of growth for the duckweed was at 93% of the control when exposed to 230 µg/L of zinc. Guar et al. (1994) reported a 96-h EC50 (growth) of 948 µg Zn/L for *Azolla pinnata.* The toxicity of zinc to algae and macrophytes seems highly dependent on species. The algae appears to be more sensitive to zinc than the macrophytes.

In field tests (submerged carboys) with plankton communities and in the water of Lake Michigan, Marshall et al. (1983) reported significant reduction in chlorophyll *a* and primary productivity when exposed to 15 µg/L of zinc. Using the modified AAP medium without EDTA (Algal Assay Procedure Bottle Test -AAPBT), Chiaudani and Vighi (1978) obtained one of the lowest 7-d EC50 (effective concentration that reduced the population growth to 50% of the control growth level) at 4.1 µg Zn/L for *S. capricornutum.* While the standard AAPBT could be applied as a reliable screening test for identification of substances that are likely to be hazardous to phytoplanktons, the authors concluded that the application of *Selenastrum* test must be tested extensively in natural waters before the same could be used widely as a standard method for toxicity evaluation. No further reference in support of this method for heavy metal toxicity identification was found in the literature. Matulova (1978) (Cited in Vymazal 1986) reported initiation of first deleterious effects on green alga *Scenedesmus quadricauda* exposed to a concentration of 2 µg/L zinc. Vymazal did not specify the nature of the deleterious effect. Also, the tests with the same species by other investigators show that much high levels of zinc (64 to 300 µg/L) are required to cause an adverse effect (Eisler 1993).

It was recognized that zinc toxicity was independent of water hardness in soft water environments, but it was significantly influenced when hardness exceeded 90 mg/L $CaCO_3$. This trend was evident from the Zn toxicity (chronic) versus water hardness plot based on the acceptable data from the literature. The proposed Canadian Water Quality Guideline (CWQG) for freshwater life is a lower bound, with an appropriate safety factor, that enveloped all toxicity data above it as well as reflected the toxicity-hardness relationship (at hardness greater than 90 mg/L $CaCO_3$). To do this, the lowest observed effect levels (LOELs) in the 0-90 mg/L $CaCO_3$ (15 µg Zn/L, Marshall et al. 1983) and 150-250 mg/L $CaCO_3$ (180 µg Zn/L, Brungs 1969) intervals were selected. The LOELs were then multiplied by an application factor of 0.5 to obtain two points on the guideline envelop. For practical reasons, it was also assumed that zinc toxicity varied linearly with water hardness above 90 mg/L $CaCO_3$.

In some instances, the ambient or existing concentration of zinc in the environment may exceed the recommended Canadian water quality guidelines. This may be true especially in the soft water (hardness ≤90 mg/L $CaCO_3$) environments. To protect aquatic life in such environments, it is recommended that degradation of the existing water quality should be avoided.

Zinc shows variable behaviour in binding to particulate matter depending upon physical chemical characteristics of the aquatic system. The literature shows that particulate zinc in rivers and lakes varied from 10-78% of total zinc (Moore and Ramamoorthy 1984). Also, soluble species of Zn are most bioavailable and most toxic (Spear 1981). This observation is also supported by other investigators. For instance, Miller et al. (1992) found that zinc concentration in water was a better predictor of the white sucker (*C. commersoni*) tissue contamination than the concentration in either sediment or invertebrates. Similar observations were also made by Campbell et al. (1985) who suggested that most of the zinc burden in stems of yellow water lily (*Nuphar variegatum*) was derived directly from the water column and not from the sediment. In view of this fact, it is recommended that the zinc guideline should be interpreted in tenns of the dissolved metal fraction when the total Zn concentration in the environment exceeds the guideline due to particulate matter and, at the same time, adverse effects are not obvious.

A smaller application factor of 0.5, instead of 0.1 recommended by the CCME (1991), was chosen because:

- Zinc is an essential element for growth of biota and very low levels of the metal may be harmful to the environment due to deficiency. For instance, Francis and Harrison (1988) observed that a freshwater sponge (*Ephydatia fluviatilis*) grew normally at 0.65 µg/L zinc, but the growth was reduced at lower concentrations. Marine algae stopped growing when ambient concentration fell below 0.7 µg/L zinc (Vymazal 1986). Spry et al. (1988) exposed rainbow trout fry simultaneously to diets containing 1, 90, or 590 mg Zn/kg and water containing 7, 39, 148, and 529 µg Zn/L. After 16 weeks, the 7 µg Zn/L plus 1 mg/kg diet group showed clear signs of deficiency including a significantly reduced plasma zinc concentration, reduced growth, and reduced plasma protein and whole-body zinc concentration.

- The application factor of 0.5 was also justified by the average ratio between the no observed effect level (NOEL; or a level near to it) and the lowest observed effect level (LOEL), in the table below, based on data found in the literature on various aquatic organisms.

NOEL/LOEL table

Species	**NOEL (µg Zn/L)**	**LOEL (µg Zn/L)**	**NOEL/ LOEL**	**Reference**
Asiatic clams (*Corbicula* sp.)	25 (control)	50 (impairment in weight gain	0.5	Belanger et al. 1986
D. magna	70 (16% reproductive impairment- 'safe conc.'	158 (3-wk LC50)	0.44	Biesinger & Christensen 1972
Lemna minor L.	80 (control)	180 (growth rate 93% of control)	0.44	Dirilgen & Inel 1994a
Mayfly larvae (*E. latifolium*)	8.8 (control)	18.8 (growth decreased to 10% in 4 wks.	0.47	Hatakeyama 1989
Brook trout (*S. fontinalis*)	534	1368 (sig. reduced embryo & larval survival)	0.39	Holcombe et al. 1979
Guppy (*P. reticulata*)	173 (female giving birth twice the control)	607 (female giving birth half the control)	0.29	Pierson 1981
Steelhead (swim-up)	54 (200-h LClO)	93 (200-h LC50)	0.58	Chapman 1978b
Chinook (swim-up)	68 (200-h LC10)	97 (200-h LC50)	0.70	Chapman 1978b
		Av. NOEL/LOEL = 0.48		

Adverse effects of zinc were reported in the literature at concentrations lower than 15 µg/L at hardness< 90 mg/L $CaCO_3$. These include, 7-d EC50 of 4.1 µg Zn/L for *S. capricornutum.* by Chiaudani and Vighi (1978), deleterious effects on green alga *S. quadricauda* exposed to 2 µg Zn/L by Matulova (1978 - Cited from Vymazal 1986), LT50 of 10 µg Zn/L for crustacean *M. macrocopa,* 28-d LC54 of 10 µg Zn/L for rainbow trout by Affleck (1952), chronic effect of 4.9-19.6 µg Zn/L to brown trout by Sayer et al. (1989). However, these data were considered unacceptable for the guideline development for reasons stated above.

The proposed guidelines are characterised as interim, since the minimum requirement for primary data was not met.

3.2 Marine Life

3.2.1 *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.

3.2.2 *Summary of Existing Guidelines*

For the protection of marine aquatic life, the U.S. EPA (1987) recommended that the 1-h average concentration of zinc (acid soluble) should not exceed 95 µg/L more than once every three years and the 4-d average concentration of zinc 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 zinc 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.

3.2.3 *Rationale*

The acute (and chronic) toxicity data for fish in the marine environment are limited. The available data show that the toxicity of zinc varied greatly in the marine species. Eisler and Hennekey (1977) reported a 96-h LC50 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 LC50 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 LC50s 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 LC50 of about 230 µg Zn/Land 5-h LC50 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 zinc was also tested in other marine species. For all age groups of the mysid (*Mysidopsis bahia*)*,* Nipper et al. (1993a,b) reported a 96-h LC50 of 360 µg Zn/L. These authors also reported much lower 48-h LC50s for copepod *Temora stylifera* ranging from 4 µg Zn/L at *23%0* salinity to 31 µg Zn/L at *32%0* salinity. Nipper et al. obtained their data on copepods from south-eastern Brazil. Their data (e.g., 48-h LC50 of 4 µg/L) were also suspect because the survival rate for the control copepod population at *23%0* salinity was lower than the acceptable value for toxicity tests; the percent copepod survival in the control chambers were 76% at *23%0* salinity and 97% at *32%0* salinity. Finally, Dinnel et al. (1989) reported 96-h EC50s 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 zinc concentration and body size, and no statistically significant difference in zinc concentrations between the sexes.

Hunt and Anderson (1989) reported 9-d EC50 (metamorphosis) of 50 µg Zn/Land 48-h EC50 (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 juveniles 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 GC50s (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 an 1-h EC50 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 ECS0 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) rep01ted 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 IC50 (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 algae (*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.

4. WILDLIFE

4.1 Recommended Guidelines

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

4.2 Summary of Existing Guidelines

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

4.3 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% ZnC12 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.

5. IRRIGATION

5.1 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 is ^{3}7.0. This guidelines replace 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.

5.2 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.

5.3 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 FeSO4 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 LC50 was estimated to be 1 010 mg Zn/kg soil. Cocoon production was a more sensitive end-point with a 56-d EC50 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 zinc to soil nematodes *Caenorhabditis elegans.* An average LC50 of 255 mg Zn/kg soil was reported for the organism in Worsham sandy loam with pH 5.1. Furthermore, the LC50 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 zinc 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 ^{3}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 ^{3}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 ^{3}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.

6. LIVESTOCK WATERING

6.1 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.

6.2 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).

6.3 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. (1987a,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. (1987a,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 (^{2} 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)

7. PARAMETRIC-SPECIFIC INFORMATION

7.1 Physical and Chemical Properties

Zinc (Zn) is a bluish-white metal that belongs to Group lib of the periodic table. It has an atomic weight of 65.38, melting point of 419.6 °C, and boiling point of 907 °C. It is composite of five stable isotopes: ^{64}Zn,

^{66}Zn, ^{67}Zn, ^{68}Zn, and ^{70}Zn, with relatives abundance of 48.9%, 27.8%, 4.1%, 18.6%, and 0.6%, respectively (Adriano 1986).

The oxidation state of Zn in natural environments is exclusively Zn(II) (or Zn^{2+}). Metallic zinc forms only in highly reducing environments (Lindsay, 1979). Zinc is intermediate between hard and soft acceptors in its chemical reaction with ligands and, therefore, forms complexes with both hard bases (oxygen donors) and soft bases (sulphur donors). As a result, zinc occurs in nature both as sulphide and carbonate ores (Moore and Ramamoorthy 1984).

The solubility of zinc compounds varies with franklinite ($ZnFe_2O_4$) and willemite (Zn^2SiO4) being the least soluble compounds. The prevalent species in groundwater, in equilibrium with willemite, were Zn^{2+} and $ZnSO_4^0$ (neutral) below pH 8.2. At pH >8.2 zinc carbonate species were dominant. Other complexes of Zn with Cl^-,F^-, Br^-, OH^-, and I^- did not contribute significantly to the total Zn in solution (Lindsay 1979, Rai and Zachara 1984).

7.2 Production and Uses

Most of the zinc produced in the world comes from ores containing zinc sulphide (ZnS) minerals; for instance, sphalerite (zinc blende). Other common Zn ores of commercial importance include, smithsonite ($ZnCO_3$), hemimorphite [calamine; $Zn_4(OH)_2Si_2O_7{\cdot}H_2O$], zincite (ZnO), willemite (Zn_2SiO_4), hydrozincite [$Zn_5(OH)_6(CO_3)_2$] and franklinite [(Fe, Zn, Mn) $(Fe, Mn)_2O_4$] (Adriano 1986). In geological strata, zinc is usually found with copper or lead deposits. According to the Canada Year Book (1994), Canada is the world's largest producer of zinc in concentrate and ranks second in zinc metal production. In 1992, Canadian zinc mine production was 1.2 billion kilograms (or 1.2 million tonnes); British Columbia, Ontario, Yukon, and North West Territories are the major producers of zinc in Canada (Survey of Mines and Energy Resources 1992).

Zinc ranks fourth among metals of the world in annual consumption, behind iron, aluminium, and copper (Adriano 1986). It is used mainly as a rust-resistant coating for iron and steel products. Galvanizing, or coating, accounts for about 48% of the world's zinc consumption (Canada Year Book 1994). It is also used in the manufacture of brass and bronze in the die casting industry. Zinc and its compounds are ingredients of many household items, including utensils, cosmetics, powders, ointments, antiseptics and astringents, paints, varnishes, linoleum, rubber, and others. They also are used in the manufacture of parchment papers, glass, automobiles tires, television screens, dry cell batteries, electrical apparatus, agricultural fertilizers as micronutrient, insecticides, hardeners in cement and concrete, in printing and dyeing of textiles, in the production of adhesives, as a flux in metallurgical operations, and as wood preservatives (Adriano 1986, Canada Year Book 1994). Zinc chloride is a primary ingredient in smoke bombs used for crowd dispersal, fire fighting exercises, and by military for screening purposes. Zinc sulphate is used as co-operative agent in fungicide and as a protective agent against zinc deficiency in soils. When sprayed in combination with copper compounds or arsenic-lead wettable powders, zinc can minimize the toxic effects of these metals on fruits such as plums, apples and peaches (Eisler 1993). Zinc is also used therapeutically in human medicine in the treatment of zinc deficiency, various skin diseases, wound healing, and to reduce pain in sickle cell anaemia patients (U.S. DHHS 1992, Eisler 1993).

7.3 Sources and Pathways for Entering into the Environment

The average concentration of zinc in igneous rocks has been estimated at 70 mg/kg, which ranks it as 24th amongst the elements found in the earth crust. In sedimentary rocks, zinc ranges from 16 mg/kg in sandstone to 95 mg/kg in shales. Some deep-sea clay sediments contain an average of 165 mg/kg of zinc (Turekian and Wodepohl 1961). Zinc is easily mobilized by weathering; hence, it is ranked high in the

"Relative Critical Index" immediately after nickel and mercury and ahead of such toxic metals as lead and cadmium (Ketchum 1975).

The worldwide weathering causes about 725 000 000 kg/annum of zinc to enter the environment. The principal sources are shale and sandstone. Soil erosion sends an estimated 25 000 000 kg/annum to the atmosphere and other natural sources (such as forest fires, sea salt sprays, volcanoes etc.) contribute an additional 18 500 000 kg/annum to the environment (Taylor et al. 1985).

Zinc is discharged into the global environment at an estimated rate of 8.8 billion kg/annum; 96% of the total is a result of human activities (Leonard and Gerber 1989, Eisler 1993). The anthropogenic input of zinc into the aquatic environment was estimated to range from 77-375 million kg/annum by Nriagu and Pacyna (1988). A comparison of the atmospheric and aquatic emissions by Pacyna et al. (1995) indicated that, for zinc and most other trace metals, the annual anthropogenic inputs into water exceeded the quantities emitted to the atmosphere. However, the largest quantities of trace metals are discharged to the terrestrial environment. Major sources of anthropogenic zinc discharges to the environment include electroplaters, smelting and ore processors, drainage from active and inactive mining operations, domestic and industrial sewage, combustion of fossil fuels and solid waste, road surface runoff, corrosion of zinc alloys and galvanised surfaces, and erosion of agricultural soils (Eisler 1993).

7.4 Environmental Concentrations

Water

The concentration of zinc 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 zinc deposits. Historical zinc concentrations should be viewed with caution. Results from clean methods with lower detection limits show that background Zn concentrations are lower than previously thought. Older high values may be the artifacts of high detection limits and artificial contamination during measurement.

At a background site in the Tsolum River on the Vancouver Island, British Columbia, Deniseger and Pommen (1995) found that the total zinc concentration ranged from less than the detection limit (0.01 mg/L) to a maximum of 0.02 mg/L; the average value of 99 measurements was 0.01 mg/L total zinc. Also, the maximum concentration of dissolved zinc at 0.01 mg/L was lower than the total concentration. Nagpal (1990) reported low levels (less than the detection limits of 0.01 and 0.005 mg/L) of total zinc in about 80% of the water samples from the Oyster River watershed. Only 7 of 185 measurements in the watershed exceeded the detection limit of 0.01 mg/L. The 3 (of 7) high concentrations at 0.29, 0.18, and 0.04 mg/L were attributed either to analytical anomaly or to possible contamination from an abandoned mine site (Nagpal 1990). In Similkameen River in central British Columbia, Swain (1990) reported total zinc concentrations ranging up to 0.005 mg/Lin uncontaminated areas.

Background zinc concentrations in unfiltered samples from the Great Lakes in Ontario ranged from 0.0003 to 0.001 mg/L (OMOE 1990). Hutchinson and Sprague (1987) reported that the mean ambient concentrations in four Muskoka region lakes ranged from 0.008 to 0.022 mg Zn/L (Muskoka region is in central Ontario and may be influenced by anthropogenic inputs). The reported range was 0.003 - 0.008 mg Zn(total)/L for the Muskoka-Haliburton lakes (Yan and Miller 1984).

The British Columbia Ministry of Environment, Lands and Parks (B.C. MELP) has reported Zn concentrations in marine waters around Vancouver and the Vancouver Island over the years as part of its Water Quality Objectives Attainment program. In 1993, the total zinc concentrations in the Indian Aim (Burrard Inlet), Pender Harbour, and Saanich Inlet ranged from <0.005 to 0.009 mg/L (25-33 m deep), <0.005 to 0.013 mg/L (1-14 m deep), and <0.005 to 0.010 mg/L (1-11 m deep), respectively. These sites are influenced by anthropogenic sources of contamination, but to a relatively lesser degree. In a relatively higher contaminated area of the Burrard Inlet, the zinc concentration ranged up to 0.035 mg/L, with an average value of <0.012 mg/L (B.C. MELP 1994).

From recent (1990s) data, high concentrations of zinc in rivers and lakes of New Brunswick were observed that ranged up to 0.036 mg/L (Cannan River) in the Kennebecasis River basins, 0.062 mg/L (St John River) in the St John River basin:Woods, 0.012 mg/L (SJR Mactaquac Headpond) in the St John River basin:Frede, and 0.030 mg/L ("Unnamed" Lake) in the Fundy West region (Emery 1996). The reason for the high zinc values in water could not be determined from the data. However, the data showed that high zinc measurements were rare and, in most basins and regions, they exceeded an arbitrarily chosen limit of 0.005 mg/L in ^{2}10% of the cases.

In 1984, a limited sampling program of 37 lakes in Halifax County, Nova Scotia (a total of 37 samples) indicated that zinc concentrations ranged from <0.0061 to 0.0294 mg/L with an average value of 0.0076 mg/L (Taylor 1996). In a study of rural well water supplies in Kings County, Nova Scotia, Moerman and Briggins (1994) reported that zinc concentration in 197 wells ranged from not detected to 1.86 mg Zn/L. In a 1991 synoptic survey of 51 lakes in the Halifax-Dartmouth Metro to determine changes in water quality compared to the 1980 survey, Keizer et al. (1993) reported that the highest concentration of trace metals (e.g., zinc) occurred in those lakes with the lowest pH (e.g., Bayers, First and Second Chain, Governor, and Long; pH <5.0). Concentrations in these lakes ranged from 0.0268 (Long) to 0.194 mg Zn/L (Bayers Lake). These results were based on single samples from a highly dynamic natural system and, therefore, require caution in interpretation (Keizer et al. 1991).

The concentration of zinc in raw waters from Quebec ranged from not detected (detection limits used were 0.01, 0.02, 0.05, and 0.1 mg/L) to 0.09 mg/L. Occasionally, high values were measured at certain sites: Candiac (11 mg Zn/L), Maskinonge (0.15 mg Zn/L), and Rigaud Puits Rue Agathe (0.3 mg Zn/L). Most of these data were collected in 1970s or early 1980s (Riopel 1996).

Recently, Windom et al. (1991) questioned the reliability of the trace metals levels reported by the U.S. Geological Survey (USGS) as a part of the National Stream Quality Accounting Network (NASQAN), because of outdated analytical techniques. The USGS reported that the unweighted mean zinc concentration in the east coast river from October 1985 to September 1988 was 0.014 mg/L (222 nmol/kg). Using modem clean analytical techniques, Windom et al. found that the unweighted mean for zinc in the east coast rivers was about 13 times lower (0.0008 mg/Lor 13 nmol/kg) than the USGS reported value. The zinc concentration in sea water, obtained using reliable techniques, ranged up to 0.0005 mg/L (8 nmol/kg) (Windom et al. 1991). The mean zinc concentrations in Lake Michigan and oceans, using modem clean analytical techniques, were reported to be ^{2} 0.0005 mg/L (Hunt et al. 1995).

Soils and Sediments

All concentrations in soils and sediments are reported on a dry weight (dw) basis.

Zinc content of a soil depends upon the nature of the parent rocks, organic matter, texture, and pH. McKeague and Wolynets (1980) reported a range of 10 to 200 mg/kg zinc for Canadian soils, with an average concentration of 74 mg/kg. In a survey of agricultural areas (296 farms) of Ontario, Frank et al. (1976) reported a mean soil zinc concentration of 54 mg/kg, with a range of 5 to 162 mg/kg. The zinc concentration was related to texture; sandy soils (40 mg/kg) were much lower in zinc than loamy soils (64 mg/kg), clayey soils (62 mg/kg), and organic soils (66 mg/kg).

Rieberger (1992a) reported zinc concentrations in uncontaminated lake sediments of British Columbia. The average concentration ranged from 62.4 mg Zn/kg (standard deviation =41.6 mg/kg) in the Southern Interior Plateau tectonic subregion to 113 mg Zn/kg (standard deviation= 46.5 mg/kg) in the Alberta Plateau tectonic region. Zinc concentrations ranging from 61.4 to 144 mg/kg in the Fraser River sediments (3 sites) and 82 to 142 mg/kg in the Boundary Bay (off-shore site) were reported (Swain and Walton 1991). These sites, located in the Fraser River estuary, are likely to be contaminated to some degree from anthropogenic activities in the area.

The B.C. Ministry of Environment, Lands and Parks has reported zinc concentration in marine sediments around Vancouver and the Vancouver Island over the years as part of its Water Quality Objective Attainment program. In 1993, the total zinc concentrations in the Burrard Inlet, and Pender Harbour sediments ranged from 79 to 985 mg/kg, and 16 to 1 370 mg/kg, respectively (B.C. MELP 1994).

Biota

Zinc concentration in biota vary with several factors that include, type of specie, tissue (e.g., muscle versus liver in fish), and sample site characteristics. All concentrations in biota are reported on a wet weight (ww) basis unless specified otherwise.

Rieberger (1992b) reported zinc concentrations in tissues of fish collected from uncontaminated lakes of British Columbia. The average concentration of zinc in the liver was about 24 mg/kg for cutthroat trout, 29 mg/kg for rainbow trout, 30 mg/kg for Dolly Varden char, 28 mg/kg for lake trout, 25 mg/kg for arctic grayling, and 23 mg/kg for mountain whitefish. The average zinc concentration in the fish muscle was much lower at 6 mg/kg in cutthroat trout, 4.3 mg/kg in rainbow trout, 3.8 mg/kg in Dolly Varden char, 3.1 mg/kg in lake trout 6.1 mg/kg in arctic grayling and 4.2 mg/kg in mountain whitefish. Deniseger et al. (1988) reported heavy metal concentrations in the tissue of fish from Buttle Lake, a lake which was subject to metal loading from acid mine drainage during 1960s and 1970s. The reported zinc levels in the Buttle Lake rainbow trout (34 mg/kg in liver, 7.6 mg/kg in muscle), cutthroat trout (23 mg/kg in liver, 4.9 mg/kg in muscle), and Dolly Varden (7.8 mg/kg in muscle) were higher than those reported for uncontaminated lakes (Rieberger 1992b). Muscle zinc concentration in lake trout and northern pike from unpolluted lakes of Ontario were in the order of 2.4 to 36.9 mg/kg (OMOE 1990).

Zinc concentration in freshwater clams varied from 48 to 120 mg/kg in *Anodonta grandis* from Ontario, and 76 to 1 360 mg/kg dw in *Elliptio complanata* from the zinc-contaminated area of Noranda, Quebec (OMOE 1990). Zinc levels ranged from 163 to 20 900 mg/kg dw in zooplankton from lakes near the smelters at Flin Flon, Manitoba (OMOE 1990). Roch et al. (1985) reported zinc levels of 105 to 1 300 mg/kg dw in zooplankton from B.C. lakes with no known source of contamination. Yan et al. (1990) reported median zinc concentration of about 100 mg/kg dw in zooplankton from 38 lakes on the Precambrian Shield in Ontario.

OMOE. (1990) reported that zinc levels in aquatic macrophyte ranged from 6 to 12 300 mg/kg dw, depending upon species and tissue sampled, and site characteristics (e.g., contaminated versus uncontaminated site).

7.5 Forms and Fate in the Environment

In freshwater with pH between 4 and 7, the free zinc ion predominantly exists as aquo ion, $(Zn(H_2O)_6)^{2+}$ (Campbell and Stokes 1985). The dominant forms of dissolved zinc in freshwater at pH 6 are the free ion (98%) and zinc sulphate (2%); at pH 9 the dominant forms are the mono hydroxide ion (78%), zinc carbonate (16%), and the free ion (6%, Eisler 1993).

Zinc in aquatic environment is adsorbed by organic substances such as humic materials and biogenic structures (i.e., cell walls of plankton) and inorganic substances such as mineral particles, clays, and hydrous oxides manganese, iron, and silicon (Spear 1981). Particulate materials in the medium may contain as little as 2% and as much as 100% of the total zinc (Sprague 1986). The U.S. EPA (1987) reported that most of the zinc discharged to aquatic environment is sorbed to inorganic and organic fractions and is eventually partitioned into sediments. Zinc in sediments is present as precipitated zinc hydroxide, ferric and manganic hydroxide precipitates, insoluble organic complexes, insoluble sulphides, and other forms. As the sediments change from a reduced to an oxidised state, sediment Zn is mobilized and released; although, the bioavailability of different forms of sediment Zn varies substantially, the mechanisms of transfer are poorly understood (U.S. EPA 1987).

In sea water, zinc exists in dissolved state, as solid precipitate, or adsorbed to particulate surfaces. The dominant species of soluble zinc at pH 8.1 are zinc hydroxide (62%), free ion (17%), the monochloride ion (6.4%), and zinc carbonate (5.8%). At pH 7, the percentage of dissolved zinc as free ion increases to 50% (U.S. EPA 1987). In the presence of dissolved organic materials, most of the dissolved Zn is present as organozinc complexes (U.S. EPA 1987). In estuaries and other marine environments, the relative abundance of zinc species changes with salinity. At low salinity, $ZnSO_4$ and $ZnCl^+$ predominate; at higher salinity, the aquo ion predominates (Spear 1981).

In soil solution, Zn^{2+}, $ZnOH^+$ and $Zn(OH)_2^0$ predominate depending on soil pH. The dominant specie is Zn^{2+} at $pH< 7.7$, $ZnOH^+$ at >7.7 pH <9.1, $Zn(OH)_2^0$ at $pH>9.1$. The complex $ZnSO_4$ can also contribute significantly to total Zn in solution. In neutral and calcareous soils the $ZnHPO_4^0$ specie may be significant depending upon pH and the activity of phosphate (Lindsay 1979). Hodgson et al. (1966) found that zinc was present in soil solution as organic as well as inorganic species.

Zinc bioaccumulate moderately in aquatic organisms, and this bioaccumulation is higher in crustaceans and bivalve species than in fish (U.S. EPA 1987, U.S. DHHS 1993). Zinc does not concentrate in plants, and it does not biomagnify through terrestrial food chain (U.S. DHHS 1993).

Andrews et al. (1989) studied the distribution of zinc in a contaminated grassland ecosystem established on metalliferous fluorspar tailings. They found that zinc concentrations in composite vegetation samples were significantly elevated at the tailing site compared to the control. Also, at both sites, levels in the dead tissue were higher than in live, this pattern being more evident on the tailings site. However, the considerable differences in soil and vegetation zinc concentrations between the tailings and an uncontaminated site were not reflected in the invertebrate and small mammal communities. It was suggested that the metabolic control over zinc retention by both invertebrate and vertebrate species at the tailing site prevented accumulation of zinc to levels much in excess of those at the control site. These findings were consistent with the view that physiological differences are more important in determining invertebrate Zn body burden than trophic level or body-size.

Johnson (1987) found that levels of trace nutrients, such as Zn and copper, in fish were independent of ambient loadings. Miller et al. (1992) also reported that zinc concentrations in white sucker (*Catostomus commersone*) tissues were significantly correlated with Zn concentration in water, but not with those in sediments or benthic invertebrates. These data suggest inability of zinc to biomagnify in the aquatic environment. Effective homeostatic regulation (with respect to internal concentration) in mammals or low potential for biomagnification of zinc has been suggested by Wren et al. (1988).

7.6 Interactions and Modifying Factors

Often several contaminants are present simultaneously in the environment. The presence of one contaminant may alter the toxicity of others to aquatic organisms. Several studies were found in the literature on the combined effects of zinc and other contaminants. However, these studies did not demonstrate a definite trend. For example, Hutchinson and Czyrska (1972) found that Zn increased the cadmium (Cd) toxicity to floating aquatic plants *L. minor* and *S. natans.*

On the contrary, Huebert and Shay (1992) reported a significant antagonism between Cd and Zn effects in the aquatic macrophyte *Lemna trisulca* cultures. According to Huebert and Shay, concentration of Zn in water, aquatic plant species, and type of culture used will influence the Zn-Cd interaction. In studying the combined heavy metal toxicity to a freshwater green algae (*Scenedesmus quardricauda*), Starodub et al. (1987) found that most copper, zinc, and lead interactions were antagonistic; however, exceptions to the rule were noted for certain Zn (250 µg/L) and Pb (3000 µg/L or 6000 µg/L) concentrations in mixture which produced additive effects. Competition between Cu, Zn, and Pb for the same functional groups in the algal exudes or at the cell surface caused a net decrease in the free ion concentrations of all three metals, which resulted in a decrease in their joint toxicity. Using marine diatoms, Brrek et al. (1980) reported that the combination of Zn and Cd ions acted synergistically (more than additive) on the growth of *Thalassiosira pseudonana* and *Skeletonema costatum* (clone Skeil-5), less than additively on *Phaeodactylum tricornutum,* and antagonistically (less than additive) on *Skeletonema costatum* (clone Skel-0).

Attar and Maly (1982) found that *Daphnia magna.* was less sensitive to the Zn-Cd mixture than the single metal concentrations. For instance, the 96-h LC50 for Cd was 5 µg/L and for Zn was 67.9 µg/L, whereas a mixture of 8.5 µg/L Cd and 53.9 µg/L Zn killed only 32% of the population in 96 h. de March (1988) studied the acute toxicity of binary mixtures of five cations (Cui^{2+}, Cd^{2+}, Zn^{2+}, Mg^{2+}, and K^{+}) to the freshwater amphipod (*Gammarus lacustris*). It was concluded that K or Mg in combination with Zn had additive effects whereas the combinations of Cu and Zn, and Cd and Zn had synergistic (more than additive) effects.

Eaton (1973) exposed fathead minnows to a series of concentrations of copper, cadmium, and zinc and reported that the lethal threshold concentration for each metal in the mixture was 0.4 or less of its individual lethal threshold. In another study, Markarian et al. (1980) reported that aluminium, at normal pH (6.6-7.7), had a mitigating influence on the toxicity of metals in mixture; the metal mixture of nickel, zinc, and copper was significantly less toxic to the white sucker fish with aluminium than without it. At the normal pH levels, aluminium may have had a coagulative effect on the other metals, rendering them less toxic (Markarian et al*.,* 1980). More recently, Parrot and Sprague (1993) reported that combinations of Cu (0-90 µg/L) and Zn (0-1 200 µg/L) acted in additive fashion when tested by Microtox®, decreasing the luminescence of the marine bacterium *Photobacterium phosphoreum* after a 30 min exposure; however, acetophenone and zinc combined had less-than-additive effect.

The International Joint Commission (UC 1981) have reviewed the environmental significance of aqueous mixtures of metals. Despite the synergistic and antagonistic behaviour of metal mixtures, depending upon environmental conditions, it was generally agreed that for most metal mixtures and other commonly-occurring constituents of sewage and industrial waste an additive model is adequate to describe the joint effect of toxicants in mixture. The EIFAC (1980) and Alabaster and Lloyd (1982) agree with the concentration addition concept for metal mixtures; also, it was concluded that there was no need to adjust the EIFAC recommended guidelines for single metals downward because the metal concentrations at the recommended levels do not appear to contribute to the toxicity of a mixture of metals (Singleton, 1987).

Calcium, magnesium, hardness, salinity, pH, temperature and other environmental factors tend to modify the acute and chronic toxic effects of zinc. They affect zinc toxicity by influencing its (zinc) availability in the aquatic environment, and by inhibiting the sorption or binding of available zinc to biological tissues. The effect of water hardness on Zn toxicity is by far the most studied factor. A summary of the influence of selected modifying factors on zinc toxicity is presented below.

Winner and Gauss (1986) reported that increase in water hardness (52 to 102 mg/L $CaCO_3$) and humic acid (zero to 0.75 mg/L) concentration reduced significantly the zinc toxicity to *Daphnia magna* when exposed to 125 µg Zn/L over a 50-d period. However, the decrease in toxicity as water hardness increased was not accompanied by a reduction in Zn bioaccumulation in the *Daphnia.* Based on data from literature, Spear (1981) showed a linear (log-log) relationship betwen LC50 and hardness for several class of fish. Wells et al. (1994) performed toxicity tests on freshwater cladoceran (*D. pulex*) using textile wastewater effluent. Their results coupled with effluent fractionation and metal (zinc, calcium, and magnesium) analyses showed that the toxicity of zinc in the effluent decreased as the hardness increased and vice a versa. Also, calcium in effluent was more protective against Zn toxicity to the *Daphnia* than magnesium. Pynnönen (1995) also reported a significant correlation between water hardness (calcium) and zinc toxicity to mature glochidial larvae of a freshwater clam *Anodonta cygnea* exposed to 100 to 1 000 µg Zn /L. These results, however, were complicated by the fact that maternal pre-exposure to Zn (500 and 1 000 µg/L) improved glochidial survival at all exposures (100-1 000 µg Zn/L).

The relationship between zinc toxicity and pH are complex in nature. In a study with rainbow trout (*O. mykiss*), Bradley and Sprague (1985), reported that changes in pH significantly altered the acute toxicity of zinc to fish. At pH 5.5, 7.0, and 9.0, zinc (as total metal) was most toxic at pH 7 and least toxic at pH 9. The low toxicity of total zinc at pH 9 resulted from formation of zinc precipitate, which is of very low toxicity to the fish. These authors also observed that the toxicity of dissolved zinc becomes increasingly important at high pH levels, especially in waters of low hardness. For instance, the toxicity of dissolved zinc increased with pH recording the lowest LC50 (30 µg/L) at pH 9 in soft water (hardness = 31 mg/L $CaCO_3$). In harder water (hardness = 386 mg/L $CaCO_3$), the trend was similar at pH ^{2}7.0, but no mortality occurred at pH 9 even when the dissolved zinc level was 40 µg/L. These authors also concluded that carbonate alkalinity did not influence acute toxicity at or below pH 7 and that hardness (and not the alkalinity) was the main protective factor against zinc toxicity. Starodub et al. (1987) reported that the toxicity of zinc and metal mixtures (Cu, Zn, and Pb) to algal growth (*S. quadricauda*) was enhanced at acidic pH. Reverse trends, that is a rise in zinc toxicity to freshwater algae *Hormidium rivulare* with pH, were reported by Say and Whitton (1977) in laboratory cultures.

Other factors that may affect zinc toxicity to aquatic life include, water temperature, salinity, dissolved oxygen, phosphate concentration, and acclimation of organisms to zinc. For instance, Zou and Bu (1994) noted that the acute concentration of zinc (48-h LC50) for the water flea (*Moina irrasa*) at pH 6.5 decreased from 73 µg Zn/L at 20°C to 44 µg Zn/L at 25°C. In a study with *Praunus flexuosus,* McLusky and Hagerman (1987) reported that an increase in salinity (from 4.5%0 to 18%0) or a decrease in temperature (from 15°C to 5°C) alone reduced the zinc toxicity to the organism. Say and Whitton (1977) reported that the toxicity of zinc to freshwater algae *Hormidium rivulare* decreases as concentrations of phosphate, magnesium, and calcium increased in the aquatic environment. Observations have been made that show the time of survival in higher concentrations of zinc increases after the fish have been acclimated for a period of time to high, but not lethal levels of zinc contamination (Spear 1981).

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Table 1. Acute toxicity of zinc to freshwater fish

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
Anguilla rostrata (American eel)	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	14.6	TLm-96hr	Rehwoldt et al. 1971
	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	20	TLm-48 hr	
	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	21.6	TLm-24hr	
Catostomus commersoni (white sucker - unfed)	~17.7 g	F,M,1	$ZnCl_2$	-	-	12.1	-	-	2.2	LC50-96 hr	Duncan & Klaverkamp 1983
	~17.7 g	F,M,1	$ZnCl_2$	-	-	12.1	-	-	2.48	LC50-72 hr	
	~17.7 g	F,M,1	$ZnCl_2$	-	-	12.1	-	-	2.96	LC50-48 hr	
	~17.7 g	F,M,1	$ZnCl_2$	-	-	12.1	-	-	5.58	LC50-24 hr	
	~17.7 g	F,M,1	$ZnCl_2$	-	-	12.1	-	-	13.3	LC50-12 hr	
Clarias lazera	subadult	S,N,2	$ZnSO_4$	6.7	90%	15.3	-	20-22	40	LC50-96 hr	Hilmy et al. 1987
	subadult	S,N,2	$ZnSO_4$	6.7	90%	15.3	-	20-22	46	LC50-72 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	15.3	-	20-22	52	LC50-48 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	15.3	-	20-22	58	LC50-24 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	9.3	-	20-22	52	LC50-96 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	9.3	-	20-22	58	LC50-72 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	9.3	-	20-22	60	LC50-48 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	9.3	-	20-22	68	LC50-24 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	18.5	-	20-22	38	LC50-96 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	18.5	-	20-22	43	LC50-72hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	18.5	-	20-22	52	LC50-48 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	18.5	-	20-22	56	LC50-24 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	25.0	-	20-22	26	LC50-96 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	25.0	-	20-22	33	LC50-72hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	25.0	-	20-22	37	LC50-48 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90%	25.0	-	20-22	41	LC50-24 hr	
Cyprinus carpio (carp)	<20 cm.	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	7.8	TLm-96hr	Rehwoldt et al. 1971
	<20 cm.	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	9.3	TLm-48 hr	
	<20 cm.	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	14.3	TLm-24hr	
Fundulus diaphanus (banded killfish)	<20 cm.	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	19.1	TLm-96 hr	
	<20 cm.	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	20.7	TLm-48hr	
	<20 cm.	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	22.6	TLm-24hr	
Jordanella floridae (flagfish)	(4-5 weeks)	F,M,1	$ZnSO_4$	7.1-7.8	8.3	25.0	42	44	1.5	LC50-96 hr	Spehar 1976
	juvenile	NA	-	-	-	-	-	-	65	LC50-96 hr	Bengeri and Patil 1986

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
Labeo rohita (cypriniform fw	adult	NA	-	-	-	-	-	-	77	LC50-96 hr	
Lebistes reticulatus (unfed)	adult male (~70mg)	S,M,2	$ZnSO_4$	8.3	5.8	22.0	85	118	240	LC25-96 hr	Sehgel & Saxena 1986
		S,M,2	$ZnSO_4$	8.3	5.8	22.0	85	118	300	LC50-96 hr	
		S,M,2	$ZnSO_4$	8.3	5.8	22.0	85	118	375	LC75-96 hr	
		S,M,2	$ZnSO_4$	8.3	5.8	22.0	85	118	212	LC25-96 hr	
		S,M,2	$ZnSO_4$	8.3	5.8	22.0	85	118	278	LC50-96 hr	
		S,M,2	$ZnSO_4$	8.3	5.8	22.0	85	118	325	LC75-96 hr	
Lepomis gibbosus (pumpkinseed)	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	20	TLm-96hr	Rehwoldt et al. 1971
	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	21.8	TLm-48 hr	
	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	25.2	TLm-24hr	
Lepomis macrochirus (bluegill)	49mm	F,M,1	$ZnSO_4$	6.8-7.5	6.6-9.5	22.0	23.2-32.8	21.2-59.2	3.2	LC50-96 hr	Thompson et al. 1980
	adult	F,M,1	-	7.5	-	15.0	18	20	5.4	LC50-96 hr	Pickering & Henderson 1966
	adult	F,M,1	-	7.5	-	15.0	300	360	40.9	LC50-96 hr	
Morone saxatilis (striped bass)	larvae	NA	-	-	-	-	-	-	0.100- [?]	LC50-96 hr	EPA 1980 & 1987
	fry	NA	-	-	-	-	-	-	0.430-1.180	LC50-96 hr	
	adult	NA	-	-	-	-	-	-	6.7	LC50-96 hr	
Oncorhyncus clarki (cutthroat trout)		NA	-	-	-	-	-	-	0.061-0.600	LC50-96 hr	EPA 1980; Mayer & Ellersieckl 1986
Oncorhyncus mykiss (rainbow trout)	fry	NA	-	-	-	-	-	-	0.090-0.093	LC50-96 hr	EPA 1980 & 1987
	parr	NA	-	-	-	-	-	30	0.24-0.83	LC50-96 hr	EPA 1980
	parr	NA	-	-	-	-	-	500	4.7	LC50-96 hr	
	parr	NA	-	-	-	-	-	350	1.19-4.52	LC50-96 hr	EPA 1980
	fry	NA	-	-	-	-	-	-	0.689	LC50-96 hr	
	0.6 g	F,M,1	-	-	-	-	-	-	0.169	LC50-96 hr	Buhl &Hamilton 1990
	juvenile	F,M,1	-	6.8	-	12	25	26	0.43	LC50-96 hr	Sinely et al. 1974
	juvenile	F,M,1	-	7.6	-	15	43	47	0.52	LC50-96 hr	Holocombe and Andrew 1978
	juvenile	F,M,1	-	7.2	-	16.0	170	179	2.96	LC50-96 hr	
	juvenile	F,M,1	-	7.8	-	15.5	-	504	4.8	LC50-96 hr	Solbe 1974
Pimephales promelas	Š24hr	S,M,2	$ZnSO_4$	7-7.5	>5	25.0	225-245	280-300	0.33	LC50-96 hr	Schubauer-Berigan 1993
	Š24hr	S,M,2	$ZnSO_4$	8-8.5	>5	25.0	225-245	280-300	0.5	LC50-96 hr	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
(fathead minnow)	Š24hr	S,M,2	$ZnSO_4$	6-6.5	>5	25.0	225-245	280-300	0.78	LC50-96 hr	
	larvae	F,M,1	-	-	-	-	-	-	0.6	LC50-96 hr	Spear 1981
	adult	F,M,1	-	7.5	-	15	18	20	0.87	LC50-96 hr	Pickering and Henderson 1966
	adult	F,M,1	-	7.5	-	15.0	300	360	33.4	LC50-96 hr	
	adult	F,M,1	-	8	-	25	57	50	4.7-6.1	LC50-96 hr	Mount 1966
	adult	F,M,1	-	8.6	-	25.0	-	100	6.4	LC50-96 hr	
	adult	F,M,1	-	8	-	25.0	162	200	8.2-21.0	LC50-96 hr	
	adult	F,M,1	-	6.2	-	25.0	-	166	7.6	LC50-96 hr	Rachlin and Perlmutter 1968
	immature 2-3	F,M,1	$ZnSO_4$	7.7	6.7	23.0	162	203	9.2	TLm-96 hr	Spehar 1976
	immature 2-3	F,M,1	$ZnSO_4$	7.7	6.7	23.0	162	203	12.5	TLm-96 hr	
Poecilia reticulata (guppy - fed)	5 days	F,M,1	$ZnSO_4$	7.16	7.9	25.1	33.5	Salinity=30	1.74	LC50-96 hr	Pierson 1981
	mature male	S,M,2	$ZnSO_4$	7.16	7.9	25.1	33.5	Salinity=30	5.05	LC50-96 hr	
	mature female	S,M,2	$ZnSO_4$	7.16	7.9	25.1	33.5	Salinity=30	6.4	LC50-96 hr	
Roccus americanus (white perch)	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	10.2	TLm-48hr	Rehwoldt et al. 1971
	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	13.6	TLm-24hr	
	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	14.3	TLm-96 hr	
Roccus saxatilis (striped bass)	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	6.7	TLm-96 hr	
	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	10	TLm-48hr	
	<20 cm	S,M,2	$ZnNO_3$	7.8	6.5	17.0	-	53	11.2	TLm-48hr	
Oncorhynchus mykiss (steelhead trout)	small (1-6 g)	F,M,1	$ZnCl_2$	7	>90%	15.0-16.0	-0.2	9.2	0.066	LC50-96 hr	Cusimano & Brakke 1986
	small (1-6 g)	F,M,1	$ZnCl_2$	5.7	>90%	15.0-16.0	1.7	9.2	0.097	LC50-96 hr	
	small (1-6 g)	F,M,1	$ZnCl_2$	4.7	>90%	15.0-16.0	11	9.2	0.671	LC50-96 hr	
	juvenile	F,N,2	$ZnSO_4$			15		soft water	0.43	LC50-96 hr	Sinley et al. 1974
	juvenile	F,N,2	$ZnSO_4$			15		hard water	7.21	LC50-96 hr	
	eyed eggs	F,N,2	$ZnSO_4$			11		soft water	2.72	LC50-96 hr	
	Eggs: *5* d post-fertilization	S,M,2	$ZnSO_4$	7.8	99.8% sat.	8.6		87.8	24	LC50-48 hr	Shazili and Pascoe 1986
	Eggs: 10 d post-fertiliz.	S,M,2	$ZnSO_4$	7.8	99.8% sat.	8.6		87.8	<1.0 (extrapolated)	LC50-48 hr	
	Eggs: 15 d post-fertiliz.	S,M,2	$ZnSO_4$	7.8	99.8% sat.	8.6		87.8	9.1	LC50-48 hr	
	Eggs: 22 d post-fertiliz.	S,M,2	$ZnSO_4$	7.8	99.8% sat.	8.6		87.8	7	LC50-48 hr	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
	Eggs: 29 d post-fertiliz.	S,M,2	$ZnSO_4$	7.8	99.8% sat.	8.6		87.8	4.3	LC50-48 hr	
	Eggs: 36 d post-fertiliz.	S,M,2	$ZnSO_4$	7.8	99.8% sat.	8.6		87.8	9.2	LC50-48 hr	
	Alevins: 2d post-hatch	S,M,2	$ZnSO_4$	7.8	99.8% sat.	8.6		87.8	3.2	LC50-48 hr	
	Alevins: 7 d post-hatch	S,M,2	$ZnSO_4$	7.8	99.8% sat.	8.6		87.8	3.4	LC50-48 hr	
Salmo trutta (brown trout)	yearlings (8-10 g)	F,M,1	$ZnSO_4$	9.11	10.1-10.3	15	103	204	0.46	LC50-96hr	Everall et al. 1989
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	7.03	10.1-10.3	15.0	103	204	0.64	LC50-96 hr	
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	7.89	10.1-10.3	15.0	103	204	1	LC50-96hr	
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	4.1	10.1-10.3	15.0	103	204	2.02	LC50-96hr	
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	5.89	10.1-10.3	15.0	103	204	2.69	LC50-96 hr	
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	5.02	10.1-10.3	15.0	103	204	3.2	LC50-96 hr	
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	8.03	10.1-10.3	15.0	62	10	<0.14	LC50-96hr	
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	9.06	10.1-10.3	15.0	62	10	0.22	LC50-96hr	
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	7.07	10.1-10.3	15.0	62	10	0.6	LC50-96 hr	
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	3.98	10.1-10.3	15.0	62	10	1.07	LC50-96hr	
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	6.01	10.1-10.3	15.0	62	10	1.41	LC50-96hr	
	yearlings (8-10 g)	F,M,1	$ZnSO_4$	5.06	10.1-10.3	15.0	62	10	2.31	LC50-96hr	
Salvelinus fontinalis (brook trout)	juvenile	F,M,1	$ZnSO_4$	-	-	15.0	-	soft water	2	LC50-96hr	Holcombe et al. 1979
	subadult	S,N,2	$ZnSO_4$	6.7		25.0	-	20-22	13	LC50-96 hr	Hilmy et al. 1987

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
Tilapia zilli (bolti)					90% sat.						
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	25.0	-	20-22		LC50-72 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	25.0	-	20-22	18	LC50-48 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	25.0	-	20-22	22	LC50-24 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	18.5	-	20-22	21	LC50-96 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	18.5	-	20-22	24	LC50-72 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	18.5	-	20-22	29	LC50-48 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	18.5	-	20-22	33	LC50-24 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	15.3	-	20-22	27	LC50-96 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	15.3	-	20-22	32	LC50-72 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	15.3	-	20-22	34	LC5048 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	15.3	-	20-22	38	LC50-24 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	9.3	-	20-22	33	LC50-96 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	9.3	-	20-22	40	LC50-72 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	9.3	-	20-22	45	LC50-48 hr	
	subadult	S,N,2	$ZnSO_4$	6.7	90% sat.	9.3	-	20-22	49	LC50-24 hr	
Oncorhynchus mykiss (steelhead trout)	adult male	F,M,1	$ZnCl_2$	7.45	10.4	10.3	55	83	1.755	LC50-96 hr	Chapman & Stevens 1978
	swim-up alevins	F,M,1	$ZnCl_2$	7.1	10.2	11.6-12.8	22	23	0.093	LC50-96 hr	Chapman 1978b
	5-8 month parr	F,M,1	$ZnCl_2$	7.3	10.2	11.6-12.8	22	23	0.136	LC50-96 hr	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
	smolts	F,M,1	$ZnCl_2$	7.1	10.2	11.6-12.8	22	23	>0.651	LC50-96 hr	
	newly hatched alevins	F,M,1	$ZnCl_2$	7.1	10.2	11.6-12.8	22	23	0.815	LC50-96 hr	
Oncorhynchus nerka (sockeye salmon)	immature	F,M,1	-	-	-	-	-	-	0.75	LC50-96 hr	Chapman 1978a
Oncorhyncus tshawytscha (chinook salmon)	juvenile	F,M,1	$ZnSO_4$	7.1-7.2	85% sat.	11-13	18-19	20-21	0.04	LC10-96 hr	Finlayson & Verrue 1982
	juvenile	F,M,1	$ZnSO_4$	7.1-7.2	85% sat.	11-13	18-19	20-21	0.084	LC50-96 hr	
	smolts	F,M,1	-	-	-	-	-	-	0.446	LC50-96 hr	EPA 1987
	swim-up alevins	F,M,1	-	7.3-7.5	10.2	11.6-12.8	22	23	0.097	LC50-96 hr	Chapman 1978b
	5-8 month parr	F,M,1	-	7.1	10.2	11.6-12.8	22	23	0.463	LC50-96 hr	
	newly hatched alevins	F,M,1	-	7.3-7.5	10.2	11.6-12.8	22	23	>0.661	LC50-96 hr	
	smoltss	F,M,1	-	7.1	10.2	11.6-12.8	22	23	0.701	LC50-96 hr	
Salmo salar (Atlantic salmon)	immature	D	-	-	-	-	-	14	0.42	LC50-96 hr	EPA 1980
	immature		-	-	-	-	-	20	0.6	LC50-96 hr	
Oncorhynchus kisutch (coho salmon)	adult male	F,M,1	$ZnCl_2$	7.4	9.8	13.7	20	25	0.905	LC50-96 hr	Chapman & Stevens 1978
	-	F,M,1	-	-	-	-	3.8	5	0.28	LC50-96 hr	McLeay 1976
	0.5-0.9 g	F,M,1	-	-	-	-	3.8	5	0.82-1.81	LC50-96 hr	
Ptychocheilus oregonesis (Northern squawfish)	juvenile ~6.6g	F,M,1	$ZnCl_2$	7.1-7.5	>8.6	12	22	23	3.498	96-h LC50	Andros & Garon 1980
	juvenile ~5.1g	F,M,1	$ZnCl_2$	7.1-7.5	>8.6	12	22	23	3.693	96-h LC50	

KEY

LC = Lethal Concentration
TLm = Lethal Threshold (50% survival)
S = Static Test Method
F = Flowthrough Test Method
M=Measured
N=Nominal
NA= Not Available
1 =Primary
2 = Secondary

Table 2 Chronic toxicity of zinc to freshwater fish

Species	**Life Stage**	**Data Type**	**Chemical**	**pH**	**(D.O. mg/L)**	**Temp. °C**	**Alkalinity (mg/L)**	**Hardness (mg/L as CaCO3)**	**Conc. (mg/L)**	**Effect**	**Reference**
Gasterosteus aculeatus (stickleback)	-	NA	$65ZnCl_2$	-	-	-	-	282	0.5-1.0	gill damage	Perwak et al. 1980
	-	NA	$65ZnCl_2$	-	-	-	-	282	1	increased oxygen uptake	
Jordanella floridae (flagfish)	all fish	F,M,1	$ZnSO_4$	7.1-7.8	8.3	25	42	44	>0.047	Fish contain higher amounts of Zn than	Spehar 1976
	females	F,M,1	$ZnSO_4$	7.1-7.8	8.3	25	42	44	0.085	significantly lower growth 30 days	
	larvae	F,M,1	$ZnSO_4$	7.1-7.8	8.3	25	42	44	0.139	zero survival in 30 days	
	life-cycle	NA	-	-	-	-			26-51	MATC	U.S. EPA (1987)
Leiopotherapon unicolor (spangled perch)	60-80 g	S,N,2	$ZnSO_4$	-	>90% sat.	25			10	sig. increase in ventilation rate	Gehrke 1988
	60-80 g	S,N,2	$ZnSO_4$	-	>90% sat.	25			20	development of a significant bryocardia	
Lepomis macrochirus (bluegill)	-	F,M,1	-						0.076-0.235	reproductive inhibition	Sparks et al. 1972
	-	F,M,1	-						0.1	hyperactivity	Ellgaard et al. 1978
	fry	NA							0.235	lethal in 3 days	EPA 1980 & 1987
Noemacheilus barbatulus (stone loach)		F,M,1							1.9-2.0	LC50-25 days	Solbe & Flook 1975
	6.5-11 cm	F,M,1	$ZnSO_4$	~7.5	~91% sat.	11.8-13.9		291-297	~2.0	LC50-7 days	Solbe and Book 1975
Oncorhyncus clarki (cutthroat trout)		F,M,1							0.36	none dead in 14 days	Nehring & Goettl 1974
		F,M,1							0.67	LC50-14 days	
Oncorhyncus mykiss (rainbow trout)	5 months 3 g wet	F,M,1	$ZnCl_2$	6.6	10	12.6	25	33	0.17	LC50-120hr	Anadu et al. 1989
	immatures	NA								avoidance, 10-20 min. ____	EPA 1980 & 1987
	life cycle	NA								MATC	EPA 1980 & 1987

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
	immatures	NA								94% avoidance, 40 min. _____	EPA 1987
	immatures	NA							0.352	hyperglycemia-9 days	
	larvae + alevins	F,M,1							0.01 (2*)	LC54-28 days	Affleck 1952
	early life-stages	F,M,1							0.070-0.140	LC5-25 days	Sinley et al. 1974
	juveniles	F,M,1							0.081	hyperglycemia-24 hr	Wagner 1980
	juveniles	F,M,1							0.210-1.120	Increased blood glucose in 7-63 days	Watson & McKeown 1976
	adults	F,M,1						360	1.12	reduced growth -85 days	
	juveniles	F,M,1							0.69	increased respiration – 24 hr	Sellers et al. 1975
	larvae & alevins	F,M,1							0.40-2.80	LC50-120 hr	Edwards & Brown 1967
	juveniles	F,M,1							0.41	LC50-14 days	Nehring & Goett 1974
	juveniles	F,M,1							0.31	LC20-14 days	
Pimephales promelas (fathead minnow)	life cycle	NA							0.078-0.145	MATC	EPA 1980 & 1987
	adult	NA							0.18	65-83% reduction in fecundity in 10 months	
	juveniles	NA							0.125	reduced growth - 7 days	EPA 1987
	larvae	F,M,1							0.152-0.294	LC84 - 8 weeks	Benoit & Holcombe 1978
	adults	F,M,1							0.48	reduced growth - 30 days	Broderius & Smith, 1979
	adults	F,M,1							0.8	LC50 - 30 days	Bengtsson 1974
	embryo-larvae	NA							0.5-1.4	50% developmental malformations -96 hr	Dawson et al. 1988

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
	embryo-larvae	NA							3.6	LC50- 6 days	Dawson et al. 1988
	10 m???	F,M,1	$ZnSO_4$	7.7	6.7	15-25	162	203	0.18	eggs/female = 17% or of ??	Brungs 1969
	same as above	F,M,1	$ZnSO_4$	7.7	6.7	15-25	162	203	0.32	eggs rarely spawned	
	same as above	F,M,1	$ZnSO_4$	7.7	6.7	15-25	162	203	0.66	eggs rarely spawned	
	same as above	F,M,1	$ZnSO_4$	7.7	6.7	15-25	162	203	1.3	30-49% of fry -20d	
	same as above	F,M,1	$ZnSO_4$	7.7	6.7	15-25	162	203	2.8	no hatching success	
Poecilia reticulatus (guppy)	-	NA	-	-	-	-	-	80	1.15	growth inhibition	Perwak. et al. 1980
	age 5 days	F,M,1	$ZnSO_4$	7.16	7.86	25	33.5	42.4	1.45	167.5-h LC50	Pierson 1981
		F,M,1	$ZnSO_4$	7.16	7.86	25	33.5	42.4	0.607	reproduction inhibited	
Oncorhychus mykiss (rainbow trout)		NA	$ZnSO_4$					13-15	0.0056	threshold avoidance level 20 min.	Perwak. et al. 1980
	1-6 g	F,M,1	$ZnCl_2$	7	>90% sat.	15-16	11		0.066	LC50-168 hr	Cusimano & Brakke 1986
	1-6 g	F,M,1	$ZnCl_2$	5.7	>90% sat.	15-16	1.7		0.097	LC50-168 hr	
	1-6 g	F,M,1	$ZnCl_2$	4.7	>90% sat.	15-16	-0.2		0.501	LC50-168 hr	
	juv. 4.5-7.5 g	F,M,1	$ZnCl_2$	6.97-7.05	9.3	15	10.8	31.3	0.11	LC50- 96 h to120 h	Bradley & Sprauge 1985
	same as above	F,M,1	$ZnCl_2$	6.97-7.05	9.3	15	8.1	30.2	0.17	LC50- 96-120 hr	
	same as above	F,M,1	$ZnCl_2$	6.97-7.05	9.3	15	23.8	31.2	0.19	LC50- 96-120 hr	
	same as above	F,M,1	$ZnCl_2$	6.97-7.05	9.3	15	8.6	387	4.46	LC50- 96-120 hr	
	same as above	F,M,1	$ZnCl_2$	6.97-7.05	9.3	15	24.3	389	5.16	LC50- 96-120 hr	
	same as above	F,M,1	$ZnCl_2$	5.46-5.59	9.3	15	<1.0	31.4	0.088	LC50- 96-120 hr	
	same as above	F,M,1	$ZnCl_2$	5.46-5.59	9.3	15	<1.0	394	9.95	LC50- 96-120 hr	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
	same as above	F,M,1	$ZnCl_2$	5.46-5.59	9.3	15	<1.0	389	11.1	LC50- 96-120 hr	
	same as above	F,M,1	$ZnCl_2$	8.97-9.01	9.3	15	23.7	30.9	4.53	LC50- 96-120 hr	
	same as above	F,M,1	$ZnCl_2$	8.97-9.01	9.3	15	32.9	373	>87.90	LC50- 96-120 hr	
	2 g fingerlings through sexual maturity 2	F,N,2	$ZnSO_4$	7.81	6.8	16.2	238	333	Š0.320	0.0% mortality - 21 months	Sinley et al. 1974
	same as above	F,N,2	$ZnSO_4$	7.81	6.8	16.2	238	333	0.64	6.4% mortality - 21 months	
	same as above	F,N,2	$ZnSO_4$	7.81	6.8	16.2	238	333	1.055	10.0% mortality - 21months	
	same as above	F,N,2	$ZnSO_4$	7.81	6.8	16.2	238	333	2.2	23.0% mortality - 21months	
	eyed eggs continuing until sexual maturity	F,N,2	$ZnSO_4$	6.8	6.8	12.7	25	26	0.011-0.547	no sig. change in egg mortality	
Salmo trutta (brown trout)	yolk-sac fry	F,M,1		4.5				soft water	0.0049-0.0196	60-95% died in18 d; ~40% with noncalcified vertebrae center	Sayer et al. 1989
Salvelinus fontinalis (brook trout)	3rd generation eggs	F,M,1	$ZnSO_4$	7.0-7.7	9.8	5.0-15.0	41.8	45.4	0.266	fragility sig. increased (p=0.05)	Holcombe et al. 1979
	2nd generation embryos	F,M,1	$ZnSO_4$	7.0-7.7	9.8	5.0-15.0	41.8	45.4	1.36	Hatchability sig. reduced (p=0.05)	
	"fresh" embryos	F,M,1		7.2-7.9	11.6	9	41.3	45.9	1.368	Survival sig. reduced (p=0.05)	
	adults	F,M,1							0.63	LC17-14 days	Nehring & Goettl 1974
	adults	F,M,1							0.96	LC50-14 days	
Oncorhynchus kisutch (coho salmon)	juvenile	F,M,1							0.5-10.7	decreased white blood cells in 24 h	McLeay 1975

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
Oncorhynchus nerka (sockeye salmon)	adult-smolt	F,M,1	$ZnCl_2$	7.2	9			35	0.03-0.112	no adverse effects-18 months	Chapman 1978a
	embryo- ???	F,M,1	$ZnCl_2$	7.2	9			35	0.242	no adverse effects-18 months	
	immatures	NA	-	-	-	-	-	-	0.447	115-h LC50	U.S. EPA 1980
Oncorhynchus tshawytscha (chinook salmon)	newly hatched alevins	F,M,1	$ZnCl_2$	7.3-7.5	10.2	~12	-	23	>0.661 0.364-661	200-h LC50 200-h LC1O	Chapman 1978b
	swim-up alevins	F,M,1	$ZnCl_2$	7.1	10.2	~12	-	23	0.091-0.068 (?)	200-h LC50; 200-h LC10	
	5-8 mon. parr	F,M,1	$ZnCl_2$	7.3-7.5	10.2	~12	-	23	0.395-0.368?	200-h LC50; 200-h LC10	
	smolts	F,M,1	$ZnCl_2$	7.1	10.2	~12	-	23	0.36; 0.170	200-h LC50; 200-h LC10	
Oncorhynchus mykiss (steelhead)	newly hatched	F,M,1	$ZnCl_2$	7.1	10.2	~12	-	23	0.555; 0.256	186-h LC50; 186-h LC10	
	swim-up alevins	F,M,1	$ZnCl_2$	7.1	10.2	~12	-	23	0.093; 0.054??	200-h LC50; 200-h LC10	
	5-8 mon. parr	F,M,1	$ZnCl_2$	7.3-7.5	10.2	~12	-	23	0.120; 0.061	200-h LC50; 200-h LC10	
	smolts	F,M,1	$ZnCl_2$	7.1	10.2	~12	-	23	0.278; 0.084?	200-h LC50; 200-h LC1O	
	embryo	F,M,1	$ZnCl_2$	6.9-7.1	>8.7	12	25	25	0.819	86% mortality in 72 d (9.6% in control)	Cairns et al 1982
	embryo	F,M,1	$ZnCl_2$	6.9-7.1	>8.7	12	25	25	0.444	18% mortality in 72 d	
	embryo	F,M,1	$ZnCl_2$	6.9-7.1	>8.7	12	25	25	0.262	8% mortality in 72 d	
Salmo salar (Atlantic salmon)	parr	-	-	-	-	-	-	-	0.05	50% avoidance - 4h	U.S. EPA 1987
	parr	-	-	-	-	-	-	-	0.1	avoidance within 20 min.	Spear 1981
	immature	-	-	-	-	-	-	-	0.1-0.5	21-d LC50	U.S. EPA 1980
Ptychochelilus oregonensis squawfish)	6.58g	F,M,1	$ZnCl_2$	7.1-7.5	>8.6	12	20	30	3.65	168-h LC50	Andros & Garton 1980
	0.51 g	F,M,1	$ZnCl_2$	7.1-7.5	>8.6	12	20	30	2.95	168-hLC50	

KEY

LC = Lethal Concentration
TLm = Lethal Threshold (50% survival)
S = Static Test Method
F = Flowthrough Test Method
MATC = Maximum Acceptable Tolerance Concentration

M=Measured
N = Nominal
NA = Not Available
1= Primary
2= Secondary

Table 3. Acute toxicity of zinc to freshwater invertebrates

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
Ancylus fluviatilis (Gastropoda)		S,M,2	$ZnSO_4$	-	-	10	-	-	3.2	LC50-96 hr	Willis, 1988
	>3mm	S,M,2	$ZnSO_4$	-	-	10	-	-	4.5	LC50-96 hr	
Artemia franciscana (brine shrimp)	embryos (emerging)	S,M,2	$ZnSO_4$	-	-	28	-	-	~65	LC50-72 hr	
Ceriodaphnia dubia	48hr	S,M,2	$ZnSO_4$	8-8.5	>5	25	225-245	280-300	0.095	LC50-48 hr	Schubauer-Berigan 1993?
	48 hr	S,M,2	$ZnSO_4$	7-7.5	>5	25	225-245	280-300	0.36	LC50-48 hr	
	48 hr	S,M,2	$ZnSO_4$	6-6.5	>5	25	225-245	280-300	>0.53	LC50-48 hr	
Cyclops abyssonun (zooplankton)	adult ~0.62 mm	S,M,2	$ZnSO_4$	7.2	sat.	10	0.58 meq/L	-	5.5	LC50-48 hr	Baudouin & Scoppa, 1974
Daphnia hyalina (zooplankton)	adult ~1.27 mm	S,M,2	$ZnSO_4$	7.2	sat.	10	0.58 meq/L	-	0.04	LC50-48 hr	
Daphnia magna (water flea)	-	NA	-		-	30	-	-	0.005-0.014	LC50-72 hr	EPA, 1987
	0-24hr	S,N,2	ZnCl2	7.74	-	-	-	45.3	0.1	LC50-48 hr	Biesinger & Christianson? 1972
	0-24hr	S,N,2	ZnCl2	7.74	-	-	-	45.3	0.28	LC50-48 hr	
	juvenile	F,N,2	ZnCl2	6.95	-	20	80	130	0.06791	LC50-96 hr	Attar and Maly, 1982
	juvenile	F,N,2	ZnCl2	6.95	-	20	80	130	0.1261	LC50-72 hr	
	juvenile	F,N,2	ZnCl2	6.95	-	20	80	130	0.42025	LC50-60 hr	
	juvenile	F,N,2	ZnCl2	6.95	-	20	80	130	0.79894	LC50-48 hr	
	juvenile	F,N,2	ZnCl2	6.95	-	20	80	130	0.86106	LC50-36 hr	
	-	NA	-	-	-	25	-		0.56	LC50-24hr	NAS, 1979 & 1985
	-	S,M,2	$ZnSO_4$	7.6	5.6	13	400	240	0.56	EC50-48 hr (immobilization)	Khangarot & Ray, 1987
	-	S,M,2	$ZnSO_4$	7.6	5.6	13	400	240	1	EC50-24 hr (immobilization)	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
	6-24 hr, cultured in hard (300 mg/L) water before testing	S,N,2	$ZnSO_4$	7.8-8.2	92-100% sat.	-	-	250	1.1	EC50-48 hr (immobilization)	Berlind & Dave, 1984
	6-24 hr, cultured in soft (50 mg/L) water before	S,N,2	$ZnSO_4$	7.8-8.2	92-100% sat.	-	-	250	1.7	EC50-48 hr (immobilization)	Berlind & Dave 1984
	6-24 hr, cultured in hard (300 mg/L) water before testing	S,N,2	$ZnSO_4$	7.8-8.2	92-100% sat.	-	-	250	3	EC50-24 hr (immobilization)	
	6-24 hr, cultured in soft (50 mg/L) water before	S,N,2	$ZnSO_4$	7.8-8.2	92-100% sat.	-	-	250	5.3	EC50-24 hr (immobilization)	
	-	F,M,1	-	-	-	5	-	-	2.3	LC50-24 hr	Spear 1981
	Newborns, 24 hr	S,N,2	-	-	-	~20	-	-	0.752	LC50-48 hr	Arambasic *et al*. 1995
Ceriodaphnia reticulata	-	NA	-	-	-	-	-	-	0.051	LC50-96 hr	EA 1987
Daphnia pulex	-	NA	-	-	-	-	-	-	0.253	LC50-96 hr	EPA 1987

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
Erpobdella octulata (leech)	>15mg	S,M,2	$ZnSO_4$	-	-	10	-	-	0.0088	LC50-96 hr	Willis 1989
	<4mg	S,M,2	$ZnSO_4$	-	-	10	-	-	0.0021	LC50-96 hr	
	adult ~0.43 mm	S,M,2	$ZnSO_4$	7.2	sat.	10	-	0.58meq/L	0.5	LC50-48 hr	Baudouin & Scoppa 1974
Helisoma companulata (ramshorn snail)**	adult	S,N,2	$ZnSO_4$	7.3	-	55°F	-	20	3.85	TLm-96 hr	Wurtz 1962
	adult	S,N,2	$ZnSO_4$	7.3	-	55°F	-	20	4.25	TLm-72hr	
	adult	S,N,2	$ZnSO_4$	7.3	-	55°F	-	20	38.5	TLm-48 hr	
	adult	S,N,2	$ZnSO_4$	7.3	-	55°F	-	20	49	TLm-24hr	
	adult	S,N,2	$ZnSO_4$	7.8	-	73°F	-	100	5.6	TLm-96 hr	
	adult	S,N,2	$ZnSO_4$	7.8	-	73°F	-	100	5.6	TLm-72hr	
	adult	S,N,2	$ZnSO_4$	7.8	-	73°F	-	100	23.4	TLm-48 hr	
	adult	S,N,2	$ZnSO_4$	7.8	-	73°F	-	100	23.4	TLm-24hr	
	adult	S,N,2	$ZnSO_4$	7.3	-	73°F	-	20	5.6	TLm-96 hr	
	adult	S,N,2	$ZnSO_4$	7.3	-	73°F	-	20	6.53	TLm-72hr	
	adult	S,N,2	$ZnSO_4$	7.3	-	73°F	-	20	8.3	TLm-48 hr	
	adult	S,N,2	$ZnSO_4$	7.3	-	73°F	-	20	56	TLm-24hr	Wurtz 1962
	adult	S,N,2	$ZnSO_4$	7.8	-	55°F	-	100	13.4	TLm-96hr	
	adult	S,N,2	$ZnSO_4$	7.8	-	55°F	-	100	13.4	TLm-72hr	
	adult	S,N,2	$ZnSO_4$	7.8	-	55°F	-	100	49	TLm-48 hr	
	adult	S,N,2	$ZnSO_4$	7.8	-	55°F	-	100	49	TLm-24hr	
Hyalella azteca	7-14days	S,M,2	$ZnSO_4$	8-8.5	>5	25	225-245	280-300	0.29	LC50-96 hr	Schubauer-Berigan, 1993
	7-14 days	S,M,2	$ZnSO_4$	6-6.5	>5	25	225-245	280-300	1.2	LC50-96 hr	
	7-14 days	S,M,2	$ZnSO_4$	7-7.5	>5	25	225-245	280-300	1.5	LC50-96 hr	
Lumbriculus variegatus	mixed-age adults	S,M,2	$ZnSO_4$	6-6.5	>5	25	225-245	280-300	>5.0	LC50-96 hr	
	mixed-age adults	S,M,2	$ZnSO_4$	7-7.5	>5	25	225-245	280-300	>5.0	LC50-96 hr	
	mixed-age adults	S,M,2	$ZnSO_4$	8-8.5	>5	25	225-245	280-300	>5.0	LC50-96 hr	
Lymnaea luteola (fw pulmonate	adult, ave.=0.5 g	S,M,2	$ZnSO_4$	7.4	6.1	32	160	195	1.68	LC50-96 hr	
	adult, ave.=0.5 g	S,M,2	$ZnSO_4$	7.4	6.1	32	160	195	3.8	LC50-48 hr	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
	adult, ave.=0.5 g	S,M,2	$ZnSO_4$	7.4	6.1	32	160	195	7	LC50-24 hr	
Moina macrocopa (cladoceran)	<24hr	S,N,2	$ZnSO_4$	6.5	-	24-27	-	-	1.17	LC50-48 hr	Wong 1992
	<24hr	S,N,2	$ZnSO_4$	6.5	-	24-27	-	-	2.04	LC50-24 hr	
Physa heterostropha (pond snail)	juvenile	NA	-	-	-	-	-	-	0.241	LC50-96 hr	EPA 1987
	adults, 12-13?	S,N,2	$ZnSO_4$	7.3	-	70°F	-	20	4.9	TLm-96hr	Wurtz 1962
	adults, 12-13?	S,N,2	$ZnSO_4$	7.3	-	70°F	-	20	4.9	TLm-72hr	
	adults, 12-13?	S,N,2	$ZnSO_4$	7.3	-	70°F	-	20	6.1	TLm--48 hr	
	adults, 12-13?	S,N,2	$ZnSO_4$	7.3	-	70°F	-	20	12	TLm-24hr	
	adults, 12-13?	S,N,2	$ZnSO_4$	7.8	-	70°F	-	100	14	TLm-96hr	
	adults, 12-13?	S,N,2	$ZnSO_4$	7.8	-	70°F	-	100	14	TLm-72hr	
	adults, 12-13?	S,N,2	$ZnSO_4$	7.8	-	70°F	-	100	16	TLm--48 hr	
	adults, 12-13?	S,N,2	$ZnSO_4$	7.8	-	70°F	-	100	18	TLm-24hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	51°F	-	20	1.34	TLm-96hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	51°F	-	20	1.34	TLm-72hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	51°F	-	20	1.92	TLm-48hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	51°F	-	20	1.92	TLm-24hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	90°F	-	20	1.55	TLm-96 hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	90°F	-	20	1.55	TLm-72hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	90°F	-	20	2.65	TLm-48hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	90°F	-	20	2.65	TLm-24hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	68°F	-	20	1.92	TLm-96hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	68°F	-	20	1.92	TLm-72hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	68°F	-	20	2.37	TLm-48 hr	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as $CaCO_3$)	Conc. (mg/L)	Effect	Reference
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	68°F	-	20	2.95	TLm-24hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	55°F	-	20	1.92	TLm-96 hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	55°F	-	20	2.37	TLm-72hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	55°F	-	20	2.37	TLm-48hr	
	3-6mm	S,N,2	$ZnSO_4$	7.3	-	55°F	-	20	2.37	TLm-24hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	51°F	-	100	1.92	TLm-96hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	51°F	-	100	1.92	TLm-72hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	51°F	-	100	1.92	TLm-48hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	51°F	-	100	4.2	TLm-24hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	90°F	-	100	4.9	TLm-96 hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	90°F	-	100	4.9	TLm-72hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	90°F	-	100	4.9	TLm-48hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	90°F	-	100	5.66	TLm-24hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	55°F	-	100	6.17	TLm-96hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	55°F	-	100	6.17	TLm-72hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	55°F	-	100	6.17	TLm-48hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	55°F	-	100	6.95	TLm-24hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	68°F	-	100	7.5	TLm-96 hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	68°F	-	100	8.66	TLm-72hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	68°F	-	100	12.2	TLm-48hr	
	3-6mm	S,N,2	$ZnSO_4$	7.8	-	68°F	-	100	15.5	TLm-24hr	

*brine shrimp which had not hatched within 72hr were considered unlikely to survive

**significant increase in effect on this smaller size group ($p<0.05$). Helisoma companulata

KEY

LC = Lethal Concentration	M = Measured
TLm = Lethal Threshold (50% survival)	N = Nominal
S = Static Test Method	NA = Not Available
F = Flowthrough Test Method	1 = Primary
	2 = Secondary

Table 4. Chronic toxicity of zinc to freshwater invertebrates

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
Ancylus fluviatilis (gastropoda)	juvenile <2 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.08	LC50-100 days	Willis 1988
	juvenile <2 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.09	LC50-90 days	
	juvenile <2 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.18	LC50-80 days	
	juvenile <2 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.19	LC50-70 days	
	juvenile <2 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.2	LC50-60 days	
	juvenile <2 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.26	LC50-50 days	
	juvenile <2 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.36	LC50-40 days	
	juvenile <2 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.54	LC50-30 days	
	juvenile >3 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.13	LC50-100 days	
	juvenile >3 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.13	LC50-90 days	
	juvenile >3 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.24	LC50-80 days	
	juvenile >3 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.33	LC50-70 days	
	juvenile >3 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.6	LC50-60 days	
	juvenile >3 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	0.86	LC50-50 days	
	juvenile >3 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	1.34	LC50-40 days	
	juvenile >3 mm	S,M,2	$ZnSO_4$	-	-	10	-	-	1.22	LC50-30 days	
	adult	S,M,2	$ZnSO_4$	-	-	10	-	-	0.1	no adverse effect on reproduction- 100 days	
	adult	S,M,2	$ZnSO_4$	-	-	10	-	-	0.18	reproduction reduced-100d	
Biomphalaria glabrata (FW	embryo	NA	-	-	-		-	-	0.5	survival reduced 50% by day 33	Munzinger & Guarducci 1988
Chironomus riparius (diptera,	larvae	S,M,2	-	7.3-7.7	-	20	-	-	0.1	Significant delay in development for all	Timmermans et al. 1992
Corbicula sp. (Asiatic clam)	adult 13-16 mm	F,M,1	$ZnSO_4$	8.31	-	25.11	49.5	70.7	0.034	30-d EC50 (growth) *sig. diff. enzyme	Farris et al. 1989
	adult 13-16 mm	F,M,1	$ZnSO_4$	8.06	-	25.11	49.8	72.3	1.1	LC50-30 days *sig. growth inhibition-20	
	juvenile & adult	F,M,1	-	~8.2	-	20.6-25.5	38.6-59.2	66.0-88.8	>0.020	sig. reduced shell & weight growth- 30d	
	juvenile & adult	F,M,1	-	~8.2	-	20.6-25.5	38.6-59.2	66.0-88.8	1	~50% mortality __________?	
Daphnia magna (water flea)	12 12hr	S,N,2	$ZnCl_2$	7.74	near sat.	-	-	45.3	0.07	3-wk EC16 (reproduction)	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
	12 12hr	S,N,2	$ZnCl_2$	7.74	near sat.	-	-	45.3	0.102	3-wk EC16 (reproduction)	Biesinger & Christensen 1972
	newborns	S,M,2	$ZnSO_4$	8.2-9.5	-		100-119	130-160	0.1	significant reduction in longevity	Winner 1981
Epeorus latifolium (mayfly)	Larvae	F,M,1	$ZnSO_4$		-	15.5	-	83 µg/L	0.1-0.3	growth inhibition- 2 weeks; all dead before__________?	Hatakeyama 1989
	Larvae	F,M,1	$ZnSO_4$		-	15.5	-	83 µg/L	fed algae with 940 µg/g	no decrease in growth rate	
	Larvae	F,M,1	$ZnSO_4$		-	15.5	-	83 µg/L	fed algae with 1380 µg/g	Wk 1: growth rate 55% of control; Wk 2: restoration of normal	
	Larvae	F,M,1	$ZnSO_4$	7.9-8.0	-	15.5	-	83 µg/L	fed algae with >2000 µg/g	growth and emergence significantly affected	
Ephydatia fluviatilis	-	F,N,2	$ZnCl_2$	7.0	-	25	-	30mg/L Ca, 30mg/L Mg	0.0065	reduced growth rate	Francis & Harrison 1988
	-	F,N,2	$ZnCl_2$	7.0	-	25	-	30mg/L Ca, 30mg/L Mg	>0.032(4*)	tissue deterioration & death (3-wk post-exposure)	
Erpobdella octulata (leech)	juveniles <4 m wet	S,M,2	$ZnSO_4$	-	-	10	-	15	0.06	LC50-70 days	Willis 1989
	adults >15 mg wet	S,M,2	$ZnSO_4$	-	-	10	-	15	0.1	LC50-70 days	
	juveniles	S,M,2	$ZnSO_4$	-	-	10	-	15	0.222	LC50-60 days	
	adults	S,M,2	$ZnSO_4$	-	-	10	-	15	0.32	inhibited reproduction 60d?	
	juveniles	S,M,2	$ZnSO_4$	-	-	10	-	*15*	0.34	LC50-50 days	
	juveniles	S,M,2	$ZnSO_4$	-	-	10	-	15	0.39	LC50-40 days	
	adults	S,M,2	$ZnSO_4$	-	-	10	-	15	0.6	LC50-60 days	
	adults	S,M,2	$ZnSO_4$	-	-	10	-	15	1.9	LC50-50 days	
	adults	S,M,2	$ZnSO_4$	-	-	10	-	15	4.8	LC50-40 days	
Hyaklla azteca (amphipod)	0-1 week	S,N,2	-	7.9-8.6	-	25	90	130	0.0056 (control)	75% survival- 6 wks 63% survival- 10 wks	Borgmann et al. 1993

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
	0-1 week	S,N,2	-	7.9-8.6	-	25	90	130	0.042	72% survival- 6 wks 51% survival-10 wks	
	0-1 week	S,N,2	-	7.9-8.6	-	25	90	130	0.108	68% survival- 6 weeks 35% survival- 10 wks (sig. diff. from control)	
Insect community	30 d of colonization on trays in Clinch	F,M,1	-	8.93	8.9	22.4	59	85	0.015 (2*)	macroinvertebrate abundance reduced by 57% within 4 days	Clements et al. 1988
Moina macrocopa (crustacean)	newborn <24 hr	S,N,2	$ZnSO_4$	6.5	-	24-27	-	-	0.01 (1*)	LT50 (time at which 50% of animals died)-	Wong 1993
	newborn <24 hr	S,N,2	$ZnSO_4$	6.5	-	24-27	-	-	0.02 (3*)	LT50- 10.00 days	
	newborn <24 hr	S,N,2	$ZnSO_4$	6.5	-	24-27	-	-	0.1	LT50- 7.33 days	
	newborn <24 hr	S,N,2	$ZnSO_4$	6.5	-	24-27	-	-	0.25	LT50- 7.67 days	
	newborn <24 hr	S,N,2	$ZnSO_4$	6.5	-	24-27	-	-	0.5	LT50- 4.25 days	
	newborn <24 hr	S,N,2	$ZnSO_4$	6.5	-	24-27	-	-	0.7	LT50- 4.50 days	
	newborn <24 hr	S,N,2	$ZnSO_4$	6.5	-	24-27	-	-	0.5	significant reduction in survivorship	
	newborn <24 hr	S,N,2	$ZnSO_4$	6.5	-	24-27	-	-	>0.700	average lifespan reduced by more than	
Orconectes virilis (Crayfish)	adult	S,M,2	$ZnSO_4$	7.1	8	18	15	26	84	LC50-2 weeks	Mirenda 1986
Physa heterotro pha	adults 12-15 mm	S,N,2	$ZnSO_4$	7.3	-	70°F		20	4.9	TLm-120 hr	Wurtz 1962
Tanytarsus dissimilis (chironomidae) insect	embryogenesis; hatching & larval?	S,M,2	$ZnCl_2$	7.5	8.7	22	43.9	46.8	0.0368	LC50-10 days	Anderson et al. 1980
		S,M,2	$ZnCl_2$	7.5	8.7	22	43.9	46.8	0.080-0.100	10% larval survival	
Cladocera: *Holopedium gibberum*		S,M,2	65Zn		7.1				0.015	sig. reduced population	Marshall et al. 1981
Total clacedora		S,M,2	65Zn		7.1				0.015	total population	
Copepoda:											
Calanoid nauplii		S,M,2	65Zn		7.1				0.015	sig. reduced population	
Cyclopoid nauplii		S,M,2	65Zn		7.1				0.015	sig. reduced population	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
Total copepoda									0.015	insig. Reduct. in population	
Rotifers:											
Keratella cochlearis		S,M,2	65Zn		7.1					sig. increase in	
Gastropus stylifer		S,M,2	65Zn		7.1					sig. reduced population	
Polyarthra vulgaris		S,M,2	65Zn		7.1					sig. reduced population	
Conochilis unicomis		S,M,2	65Zn		7.1					sig. reduced population	
Collotheca mutabilis		S,M,2	65Zn		7.1					sig. reduced population	
Total rotifers										insig. Reduct. in population	
Euglena gracilis		S,N,2	Zn^{2+}	-	-	21-28	-		0.0075	significant decrease in mean population size	Mills 1976

KEY

LC= Lethal Concentration	M = Measured	S = Static Test Method
TLm = Lethal Threshold (50% survival)	N = Nominal	F = Flowthrough Test Method
EC= Effective Concentration	NA = Not Available	
LT=Median Age of Death	1=Primary,2=Secondary	

Table 5. Chronic toxicity of zinc to freshwater algae and macrophytes

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
Azalla filiculoides (water fern)	25 g wet	S,N,2	$ZnSO_4$	-	-	27-day, 22-night	-	-	10.0-13.0	Growth rate=44% of control in 7 d	Sela et al. 1989
	25 g wet	S,N,2	$ZnSO_4$	-	-	27-day, 22-night	-	-	12.6	Acetylene reduction (1.9% of control in 5 d	
Azolla pinnata (macrophyte)	-	S,N,2	$ZnSO_4$	7	-	25.0	-	-	0.948	EC50-96 hr (growth)	Guar et al. 1994
Cladophora glomerata (green alga)	growths of similar size, age and condition were selected.	F,M,1, river simulation velocity- after 3 hr exposure to {Zn}, Cladophora recovered in Chu 10 medium for 1 week, and was then observed.	$ZnSO_4$	-	-	-	-	-	0.4	First toxic signs, 2 of 4 samples showed cytoplasmic abnormalities	Mchardy & George 1990
	same as above	same as above	$ZnSO_4$	-	-	-	-	-	1	2 samples had damanged filaments	-
	same as above	same as above	$ZnSO_4$	-	-	-	-	-	1.75	all 4 samples displayed evidence of toxicity	-
	same as above	same as above	$ZnSO_4$	-	-	-	-	-	4	2 of 4 samples had 99% of their filaments completely colourless	-
Eichhornia crassipes (water hyacinth)	mature plants	S,N,2	$ZnSO_4$	-	-	28-30	-	-	9	30% weight reduction	Delgado et al. 1993

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
Euglena gracilis (algae)	-	S,N,2	$ZnCl_2$	-	-	25	-	-	50µM	strong inhibition of O_2 evolution- 10 days	DeFilippis & Ziegler 1993
Lemna trisulca (submerged aquatic macrophyte)	-	S,M,2	-	7.8-8.3	-	28	-	-	>0.195-0.293	decrease in multiplication rate	Huebert & Shay 1992
	-	S,M,2	-	7.8-8.3	-	28	-	-	0.325	EC50 (final yield)	
	-	S,M,2	-	7.8-8.3	-	28	-	-	0.915	EC (multiplication _____)	
Lemna minor (aqua. macrophyte)	-	S,N,2	-	-	-	25-28	-	-	10; 0.23	IC50 (10 mg/L); growth at 93% of control	Dirilgen and Inel 1994a,b
Scenedesmus quadricauda (green algae)	-	S,M,2	$ZnSO_4$	8	-	constant	-	-	0.25	EC50-4 hr (photosynthesis)	Starodub et al. 1987
	-	S,M,2	$ZnSO_4$	4.5	-	20	-	-	0.1	Growth rate- 15 days= 0.100 (sig. different from control)	
	-	S,M,2	$ZnSO_4$	6.5	-	20	-	-	0.1	Growth rate- 15 days= 0.101	
	-	S,M,2	$ZnSO_4$	8.5	-	20	-	-	0.1	Growth rate- 15 days= 0.122	
	-	S,M,2	$ZnSO_4$	4.5	-	20	-	-	0.225	Growth rate- 15 days= 0.040 (sig. different from control)	
	-	S,M,2	$ZnSO_4$	*6.5*	-	20	-	-	0.225	Growth rate- 15 days= 0.042 (sig. different from control)	
	-	S,M,2	$ZnSO_4$	8.5	-	20	-	-	0.225	Growth rate- 15 days= 0.131	
	-	S,N,2	$ZnSO_4$	4.5	-	20	-	-	0.5	Growth rate- 15 days= 0.000 (sig. different from control)	
	-	S,N,2	$ZnSO_4$	6.5	-	20	-	-	0.5	Growth rate- 15 days= 0.026 (sig. different from control)	
	-	S,N,2	$ZnSO_4$	8.5	-	20	-	-	0.5	Growth rate- 15 days= 0.109 (sig. different from control)	
	-	-	-	-	-	-	-	-	0.002	first deleterious effect	Matulova 1978
Selanastrum capricomutum (green alga)	-	NA	-	-	-	-	-	-	0.03 (2*)	Some growth inhibition- 7d	EPA 1980
	-	NA	-	-	-	-	-	-	0.040-0.068 (3*)	95% growth inhibition- 14 d	
	-	NA	-	-	-	-	-	-	0.1	100% growth inhibition- 7 d	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Alkalinity (mg/L)	Hardness (mg/L as CaCO3)	Conc. (mg/L)	Effect	Reference
	-	S,M,2, AAPBT medium	$ZnCl_2$	6.8-7.2	-	24	8.2	14.9	0.03 (2*)	Initiation of growth rate inhibition	Bartlett et al. 1974
	-	as above	$ZnCl_2$	6.8-7.2	-	24	8.2	14.9	0.12	Complete inhibition of growth rate	
	-	as above	$ZnCl_2$	6.8-7.2	-	24	8.2	14.9	0.12	Complete inhibition of growth rate	
	-	as above	$ZnCl_2$	6.8-7.2	-	24	8.2	14.9	0.12	algicidal	
	-	S,N,2	$ZnSO_4$	6.0-6.3	-	24	-	-	0.0041	7-d EC50	Chiaudani & Vighi, 1978
Spirodela olyrhiza	-	S,N,2	$ZnSO_4$	7	-	25	-	-	0.935	EC50-96 hr (growth)	Guar et al. 1994
Plankton community (Lake Michigan)	submerged carboys	S,N,2	-	-	-	-	-	-	0.015	Signific. reduction in chlorophyll *a*, primary productivity, DO, zooplankton diversity & populations and ___________?	Marshall et al. 1983

KEY

EC = Effective Concentration
S = Static Test Method
F = Flowthrough Test Method
M=Measured
N=Nominal
NA= Not Available

F = Flowthrough Test Method
IC= Inhibition Concentration
NA= Not Available
1 = Primary
2 = Secondary

Table 6. 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
Thymallus arcticus (Arctic grayling)*	0.2-1.8 g	-	-	-	-	-	-	0.112-0.168	LC50-96 hr	Buhl & Hamilton 1990
	fry	-	-	-	-	-	-	0.315	LC50-96 hr	
	alevins	-	-	-	-	-	-	1.38-2.02	LC50-96 hr	

*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 7. 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 8. 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-Aoostoloooulou 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 9. 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)	
Arbacia punctulata sea urchin	spermatozoa	NA	-	-	-	-	-	0.081	decreased motility	Perwak et al. in EPA 1980
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 ____________)	
fed	larvae	S,M,2	$ZnSO_4$	-	-	20-22	29	0.25	52% of eggs developed into larvae. (relative to ____________)	
fed	larvae	S,M,2	$ZnSO_4$	-	-	20-22	29	0.5	10% of eggs developed into larvae. (relative to ____________)	
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 ______	-	-	-	-	-	20.8	EC50 (24-h exposure plus six weeks postexposure); none dead during _______	
	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
*Rhithropanopeus harrisi (*crab)	larvae	NA	-	-	-	-	-	0.05	delayed development	Perwak et al. 1980
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	

Species	Life Stage	Data Type	Chemical	pH	(D.O. mg/L)	Temp. °C	Salinity (‰)	Conc. (mg/L)	Effect	Reference
	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 10. 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
	-	NA	-			-		0.2	growth inhibition	Perwak et al. 1980

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
S = Static Test Method
F = Flowthrough Test Method

M=Measured
N=Nominal
NA= Not Available
1 =Primary
2 = Secondary

Table 11. Zinc Criteria/Guidelines for the Protection of Aquatic Life

Statement	**Year**	**Conditions**	**Criterion/ guideline (µg/L)**	**Jurisdiction**	**Reference**
Maximum concentration to protect aquatic life	1979	at all hardness	30	Canada	CCREM 1987
One-hour average concentration to protect aquatic life	1987	hardness (mg/L $CaCO_3$) 50 100 200	65 120 210	EPA*	USEPA 1986
4-d average concentration		50 100 200	59 110 190		
24-hour average to protect aquatic life	1987	at all hardness	47	EPA	USEPA 1987
Maximum concentration to protect aquatic life	1990	at all hardness	16	Ontario	Wren et al, 1990
Maximum concentration to protect aquatic life	1983		47	Manitoba	Trotter 1987
Maximum concentration to protect aquatic life	1984		47	Quebec	Trotter 1987
Maximum concentration to protect aquatic life	1977		50	Alberta	Trotter 1987
Maximum concentration to protect aquatic life	1983		50	Saskatchewan	Trotter 1987
Maximum concentration to protect aquatic life	1992		Increase not to exceed 10% of background levels	Northwest Territories	Trotter 1987
Average of maximum concentration	1987	hardness (mg/L $CaCO_3$) 10 50 100	14 54 98	Michigan**	Zugger 1988
Average of maximum concentration	1984	hardness (mg/L $CaCO_3$) 10 50 100 500	8 50 75 125	United Kingdom	Mance & Yates 1984
Maximum annual 95-percentile concentration of zinc for salmonids	1982	hardness (mg/L C aCO_3) 10 50 100 500	30 200 300 500	Europe	EIFAC 1973

*1-h ave.: Zn(µg/L) = exp(0.8473 (ln(hardness)) + 0.8604)
*4-d ave.: Zn(µg/L) = exp(0.8473 (ln(hardness)) + 0.7614)
*** From formula: Zn(µg/L) = exp(0.85 (ln(hardness)) + 0.67) (Zugger 1988)

Table 12 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 ,)	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)	0.5mg/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
Sporophytes (Polytrichum commune)	EC50 = 4 mg/L; EC100 = 40 mg/L	Concentrations causing a 50% (EC50) and 100% (EC100) decrease in spore germination from the control value	Solution culture (petri dish)	Francis & Petersen, 1989
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

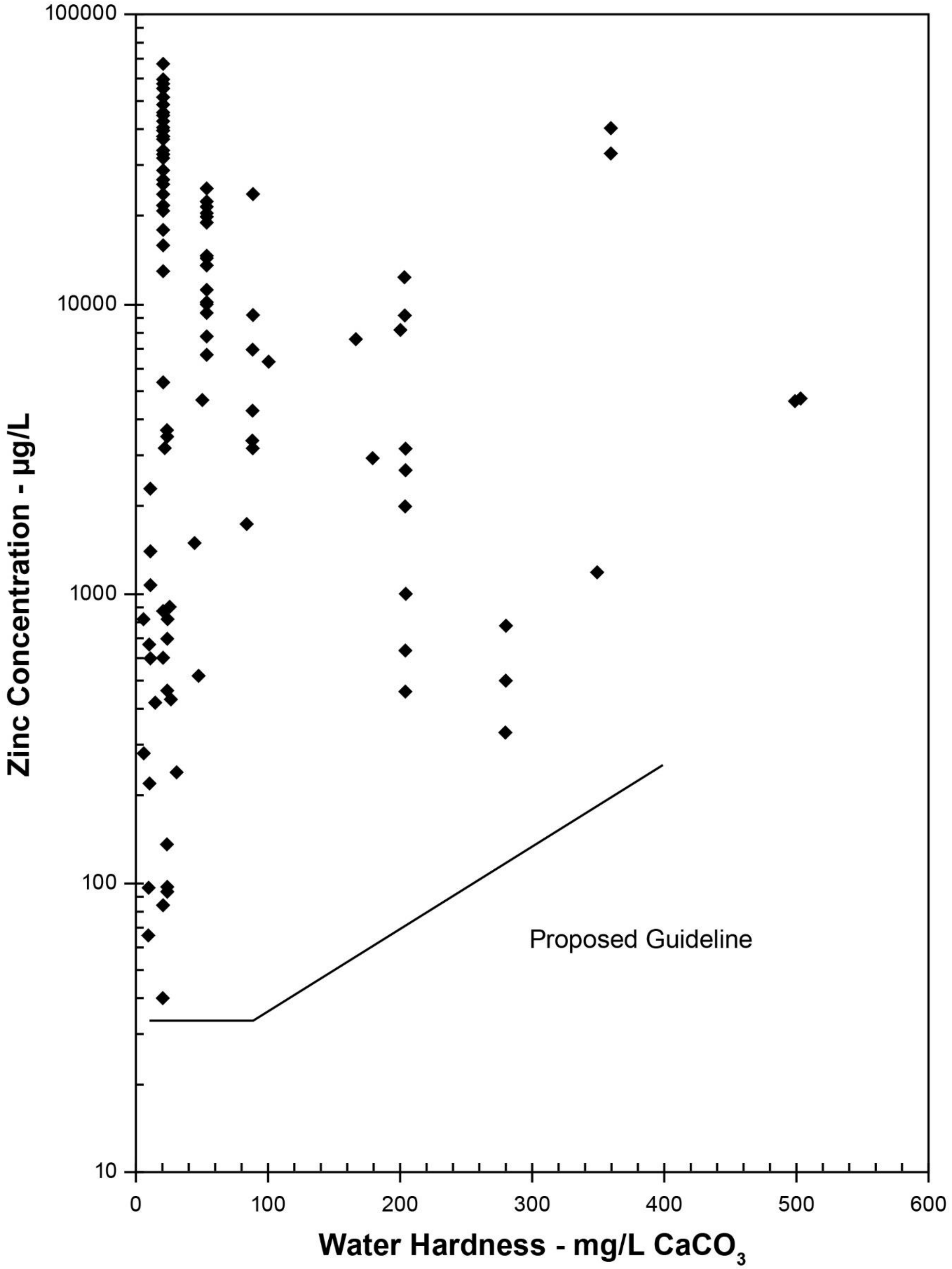

Figure 1. Acute Toxicity of Zinc vs Water Hardness

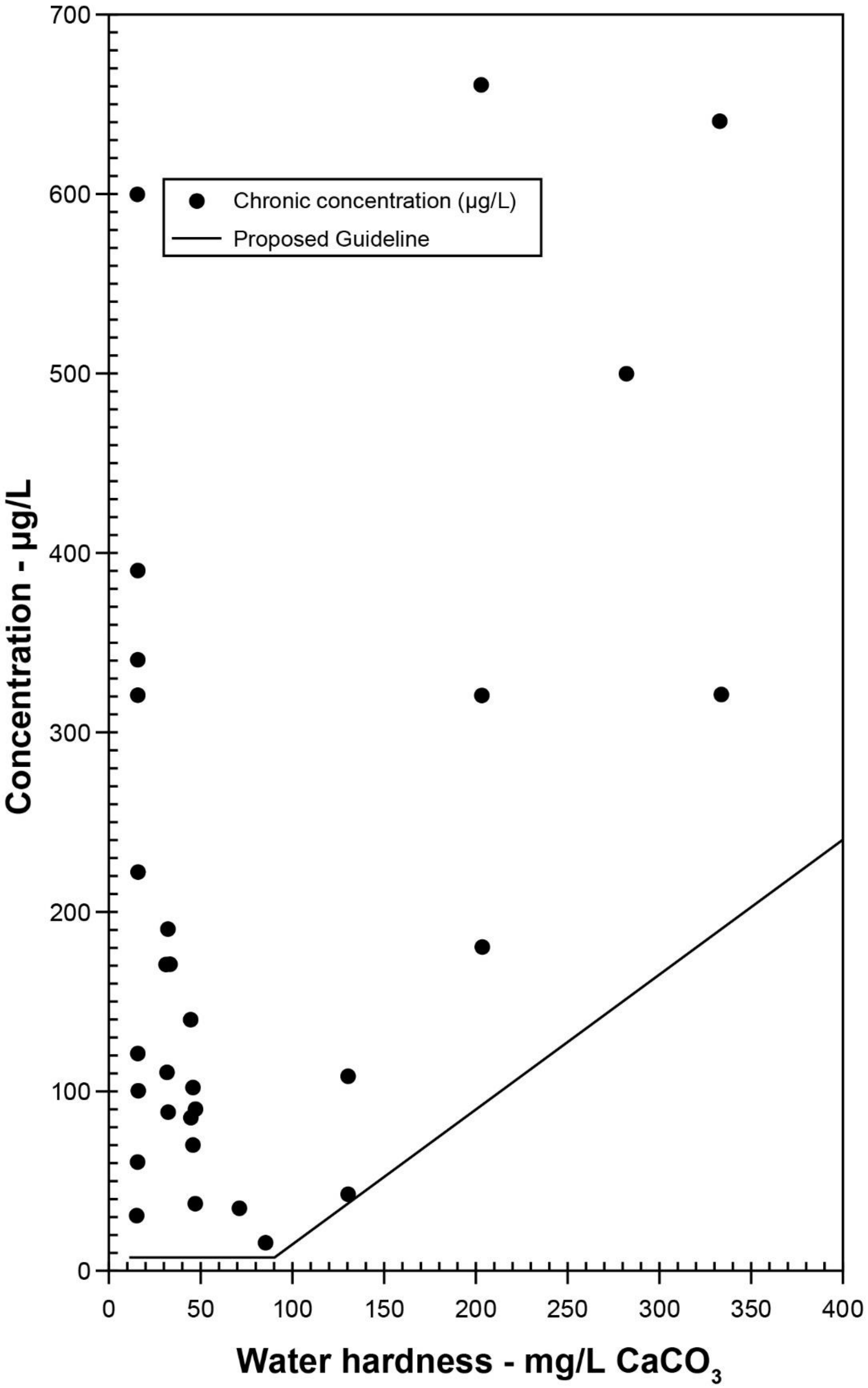

Figure 2. Zn toxicity (chronic) as a function of water hardness Water hardness - mg/L $CaCO_3$

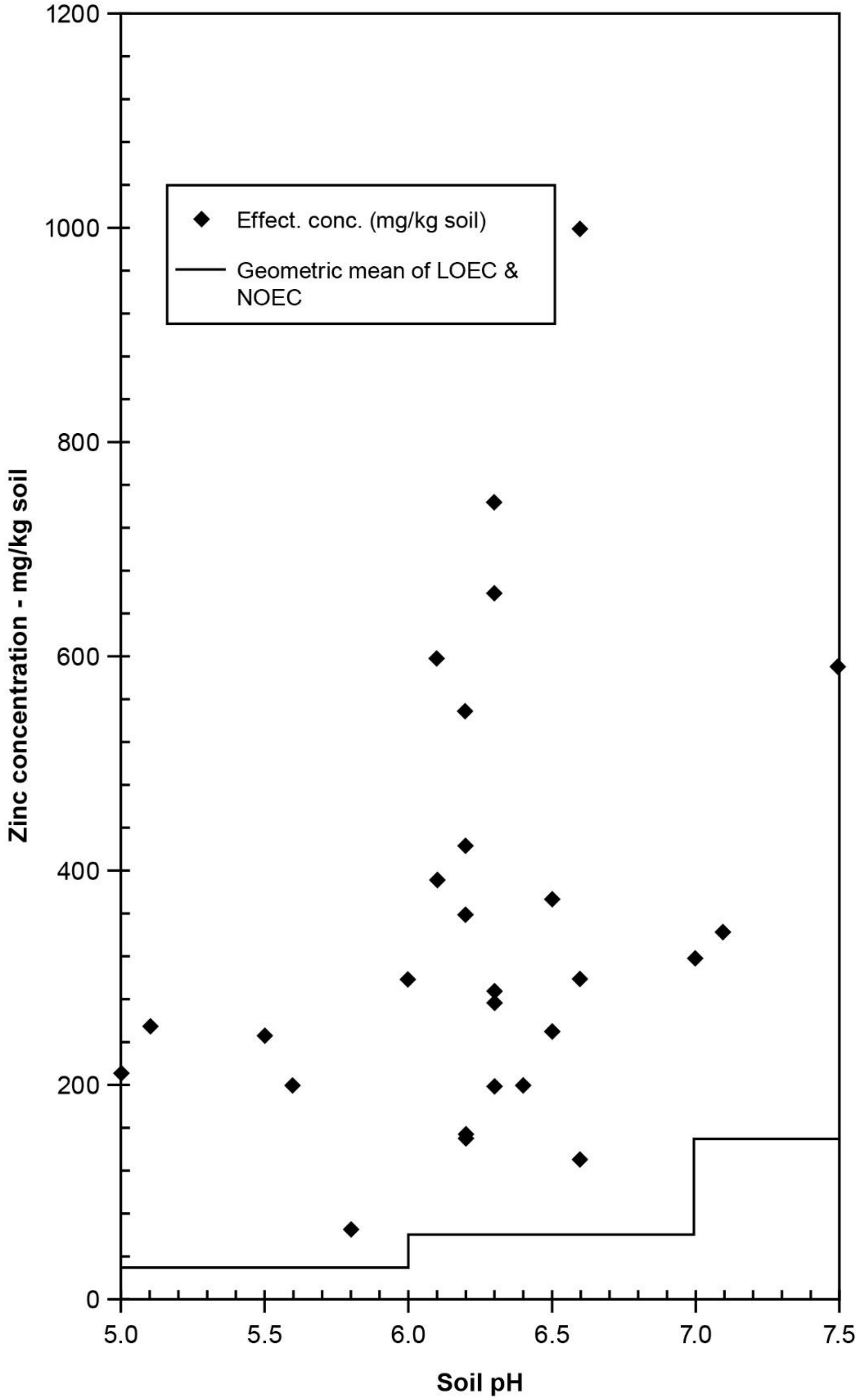

Figure 3. Zinc toxicity and geometric mean of lowest and no observed effect level