ATTACHMENT

TOXICITY PROFILES FOR CONTAMINANTS OF CONCERN

TOXICITY TO AQUATIC ORGANISMS

ORGANICS

ALUMINUM

Aluminum (Al), the third most abundant element, is found in the earth's crust at approximately 8 mg/kg (Krueger et al., 1984). Its natural occurrence is restricted to highly insoluble complex minerals (Freeman and Everhart, 1971). Upon contact with acidic water, aluminum becomes more soluble and available to local flora and fauna (Havas, 1985) by complexing with hydroxide, fluoride and organic ligands (Baker and Schofield, 1982). It can be highly toxic to aquatic biota under some circumstances, but its toxicity is strongly dependent on pH, hardness, and organic matter content. In general, the more sensitive an organism is to a low pH, the stronger the toxic response to Al concentrations with falling pH levels (Baker and Schofield, 1982). Aluminum is amphoteric, i.e., it is more soluble in both acidic and basic solutions than in approximately neutral solutions, with its highest toxicity occurring around pH 5.5 (Freeman and Everhart, 1971, Baker and Schofield, 1982). EPA's water quality criteria for aluminum (EPA, 1988-Al) assume a pH range of 6.5 to 9.0 within which aluminum occurs primarily in the form of monomeric, dimeric, and polymeric hydroxides. Toxicities of aluminum in the field may be substantially lower than indicated by dissolved aluminum analysis values because of complexation with humic and fulvic acids. At pH values below 6.5, however, aluminum may be substantially more toxic than indicated by the EPA criteria because low pH favors the formation and solubilization of cationic aluminum (Al^{3+}). The aquatic toxicity tests discussed below and used to calculate the "National Ambient Water Quality Criteria "(NAWQC) for aluminum is relevant to situations in which an acidic solution of aluminum is neutralized in ambient water forming the hydroxide flocs reported to occur in the tests. This might be the case for an acidic waste or an acidified tributary entering a well-buffered stream or lake. Their relevance to other situations is questionable.

Acute Toxicity. Between pH 6.5 and 9.0, acute toxicities of aluminum reported by EPA (1988-Al) ranged between 1.8 mg/L for *Ceriodaphnia elegans* and >79.9 mg/L for midge larvae (*Tanytarsus dissimilis*). Acute toxicities for fish ranged from 3.6 mg/L to >50.0 mg/L. Acute toxicity tests of aluminum on the nematode, *Caenorhabditis elegans*, ranged from 1.8 to 79 mg/L (Williams and Dusenbery, 1990). At pH 4.5, Freda et al. (1990) found that the 96h LC50 for *Bufo americanus* tadpoles is 0.63 mg/L. Dissolved organic compounds (5.7 mg/L) raised the LC50 of *Rana pipens* tadpoles from 0.47 mg/L Al to >0.98mg/L (Freda et al., 1990). Sublethal stress in three-week old *Rana pipens* tadpoles exposed to 0.5-1.0 mg/L Al (pH 4.8) include lowered body sodium concentration, down 26-34% of initial concentration (Freda and McDonald, 1990). The 96h LC50 for the *R. pipens* tadpole was found to be slightly greater than 1.0 mg/L Al. At pH 4.4, *R. temporaria* exhibited a 96h LC50 of 1.6 mg/L Al (Cummins, 1986)(Table 1).

Chronic Toxicity. Chronic values for aluminum in circumneutral water reported by EPA (1988-Al) ranged from 0.742 to 3.29 mg/L for aquatic organisms. In one such study, rainbow trout exposed for 45 days to 0.5 and 5.1mg/L Al (nominal pH 7.0) averaged 32.5 and 24.1% of the control weight, respectively (Freeman and Everhart, 1971). However, if acidified water is present (pH<6.5) the following results should be considered. At pH 4.5 and 5.5 aluminum (0.3 mg/L for 67d) induced fatal behavioral development in brook trout; decreased swimming response, ability to feed and ability to evade predators. Mortality of brook trout eggs was not influenced by the aluminum concentration (0.3 mg/L) at pH between 5.5 and 7.2. However, at pH 4.5, 54.4 $^+/_-$ 17.2% of the eggs did not survive (0.3 mg/L Al) after 67d (Cleveland et al., 1986). Baker and Schofield (1982) found that Al (0.1-0.5 mg/L) in acidic solutions (pH 4.6-7.06) decreased survival and growth of white sucker larvae after 13d exposure. In contrast, 95% of all post larval brook trout survived at pH 4.2-5.5 when no Al was added.

Toxicity to Aquatic Plants. Aluminum inhibited the growth of the diatom, *Cyclotella meneghiniana,* at 0.810 mg/L and caused mortality at 6.48 mg/L (Rao and Subramanian, 1982, cited in EPA, 1988-Al). Concentrations of aluminum ranging from 0.40 to 0.90 mg/L were chronically toxic to the green algae, *Selenastrum capricornutum.* At concentrations ranging from 0.02 to 0.20 mg/L Al^{3+} the growth and activity of acid photophase of *S. capricornutum* were significantly inhibited. The activity of G6PDH was decreased at Al^{3+} levels higher than 0.02 mg/L (Kong and Chen, 1995).

Bioaccumulation. Estimated steady state bioconcentration factors for aluminum in brook trout, which were inversely related to pH, were 215 at pH 5.3, 123 at pH 6.1 and 36 at pH 7.2 (Cleveland et. al., 1991). Bioaccumulation was pH dependent, with a maximum at pH 6.5 and minimum at pH 4.5. Al was found at 350, 3,000, and 11, 000μg/g BW at exposure concentrations of 0.02, 0.32 and 1.02mg/L (pH6.5) in *D. magna* (Havas, 1985). Based on body dry weight, Pynnonen (1990) found a bioconcentration factor ranging from 166.8 to 414.3 in freshwater clams, *Unio pictorum.* After a three week exposure to 0.3 mg/L Al, high accumulation of aluminum in the kidney suggest that it is the final target organ, while low level presence of Al on the gills identifies the presence of metals in the sample area.

Aquatic Mode of Action. The exact mechanisms of aluminum's physiological effects are still under investigation and not completely understood. Mortality of fish exposed to aluminum.and low pH may be the result of respiratory stress caused by gill damage, mucous clogging of the gill membrane, to the loss of sodium and chloride ions (Brumbaugh and Kane, 1985) and to the adsorption and nucleation of aluminum polymers at surface interfaces (Baker and Schofield, 1982). Aluminum may hamper the activity of calmodulin which is active in numerous biochemical processes (Siegel and Haug, 1983 cited in Lewis et al. 1990). It has been shown that trace-metals, such as aluminum, compete with H^+ for exchange sites on the gill surface (Pagenkopf, 1983 cited in Havas, 1985). Muniz and Levistad (1980 cited in Lewis et al. 1990) found that the presence of aluminum increased the loss of chloride from plasma and decreased blood oxygen tension in the brown trout. The fact that aluminum uptake and mortality increase with higher pH levels may indicate that the Al ion may bind or precipitate on biological membranes (Freda and McDonald, 1990). Verbost et al. (1992) showed that the inhibition of calcium uptake by the common carp is time and doseage dependent (>0.1 mg/L Al). In highly acidic waters, aluminum decreases RNA syntheses which may be due to disruption or deactivation of metabolic pathways (Cleveland et al., 1986). Observable effects include coughing response, hyperventilation and excessive mucus clogging of gills. Sublethal concentrations of aluminum have been shown to cause histopathological changes in the liver, kidney, skin, muscle, and gills and interfere with reproductive physiology in trout. Many studies have shown that aluminum may inhibit or render useless the hatching enzyme that digests the vitelline membrane in *Rana pipens* embryos (Katagiri, 1976, Yoshizaki, 1978, Freda and Dunson, 1984, Clark and LaZerte, 1985). In *Daphnia magna,* it has been shown that aluminum interferes with salt regulation and leads to death when sodium and chlorine concentrations are reduced (Havas, 1985).

Water Quality Criteria. NAWQC indicated that freshwater aquatic organisms and their uses should not be affected unacceptably, when the pH is between 6.5 and 9.0, if the four-day average concentration of aluminum does not exceed 0.087 mg/L more than once every three years on the average and if the one-hour average concentration does not exceed 0.750 mg/L more than once every three years on the average (EPA-Al, 1988).

Table 1. Toxicity of aluminum to aquatic organisms in circumneutral water (EPA, 1988-Al)*.

Conc.[a] (mg/L)	Effect
>79.9	Midge larvae (*Tanytarsus dissimilis*) LC50
79.0	Nematode (*Caenorhabditis elegans*) 24hr LC50
>50.0	Green sunfish (*Lepomis cyanellus*) LC50
>49.8	Yellow perch (*Perca flavescens*) LC50
>47.9	Channel catfish (*Ictalurus punctatus*) LC50
40.0	Chinook salmon (*Oncorhynchus tshawytsca*) LC50
38.2	Water flea (*Daphnia magna*) EC50
36.9	Water flea (*Ceriodaphnia sp*) 48h LC50 (Call et al. 1984)
35.0	Fathead minnow (*Pimephales promelas*) LC50
30.6	Snail (*Physa sp.*) LC50
>23.0	Planaria (*Dugasia tigrina*) LC50
>22.6	Stonefly (*Acroneuria sp.*) LC50
22.0	Amphipod (*Gammarus pseudolimnaeus*) LC50
10.4	Rainbow trout (*Oncorhynchus mykiss*) 24h LC50
8.60	Rainbow trout (*Oncorhynchus mykiss*) 96h LC50 (Call et al.1984)
3.69	Water flea (*Ceriodaphnia sp.*) EC50
3.60	Brook trout (*Salvelinus fontinalis*) LC50
3.29	Fathead minnow (*Pimephales promelas*) CV
>3.00	Rotifer (*Brachionus calyciforus*) 24h LC50 (Snell et al. 1991)
2.00	Nematode (*Caenorhabditis elegans*) 48hr LC50
1.91	Water flea (*Ceriodaphnia dubia*) CV
1.90	Water flea (*Ceriodaphnia dubia*) EC50
1.90	Nematode (*Caenorhabditis elegans*) 72hr LC50
1.80	Nematode (*Caenorhabditis elegans*) 96hr LC50
0.75	Acute NAWQ
0.74	Water flea (*Daphnia magna*) CV
0.09	Chronic NAWQ

*unless otherwise cited
[a]- concentrations given as Al, not the compound

BARIUM

Barium (Ba) is found in the more common mineral forms barite ($BaSO_4$) and witherite ($BaCO_3$) (Oehme, 1979). Barium fluorosilicate and carbonate are forms often used as pesticides. Approximately 400 mg/kg of barium is found in the earth's crust. Some plants accumulate barium from the soil. Barium has industrial applications in areas such as paper manufacturing, fabric printing and dyeing, synthetic rubber production, and drilling fluids. Barium in groundwater has been found to range from 0 to over 20 mg/L (Gilkeson et al., 1983)

Acute Toxicity. There is relatively little information of the aquatic toxicity of barium. Acute values range from a 96h LC50 for the mosquitofish *(Gambusia affinis)* (Wallen et al, 1957) to a 48h EC50 for *D. magna* (Biesinger and Christensen, 1972) (Table 2).

Toxicity to Aquatic Plants. The calculated 50% inhibition concentration was 25mg/L for duckweed (pH 6.32-8.32) in various ambient waters. The magnitude of barium's toxicity towards aquatic plants was shown to be highly dependent upon site-specific water quality characteristics and doseage (Wang, 1988). Barium inhibited calcification of the freshwater green alga *Goeotaenium* at 50.0 mg/L (Prasad, 1984).

Bioaccumulation. Barium is bioconcentrated from water by algae and vascular plants at levels dependent upon the particular species. However, Ba is not bioaccumulated through food chains and barium levels in higher species rarely exceeds 10mg/kg (Moore, 1991).

Water Quality Criteria. The state of Illinois has a water quality standard for indigenous aquatic life of 5.0 mg/L (Wang, 1988). Calculated Tier II values are SAV- 113.6 and SCV- 4.0 (Suter and Tsao, 1996).

Table 2. Toxicity of barium to aquatic organisms.

Compound	Conc.[a] (mg/L)	Species	Effect	Reference
$BaCO_3$	6950.0	Mosquitofish *(Gambusia affinis)*	96h LC50	Wallen et al. 1957
$BaCl_2$	3980.0	Scud *(Gammarus pulex)*	24h LC50	Vincent et al 1986
$BaCl_2$	1080.0	Mosquitofish *(Gambusia affinis)*	96h LC50	Wallen et al. 1957
$BaCl_2$	150.0	Brown trout *(Salmo trutta)*	96h LC50	Woodiwiss and Fretwell 1974
$BaCl_2$	122.0	Scud *(Echinogammarus berilloni)*	96h LC50	Vincent et al 1986
	113.6		SAV	Suter and Tsao, 1996
$BaCl_2$	78.0	Crayfish *(Orconectes)*	96h LC50	Boutet and Chaisemartin 1973
$BaCl_2$	46.0	Crayfish *(Austropotamobius pallipes)*	96h LC50	Boutet and Chaisemartin 1973
$BaSO_4$	33.7	Tubificid worm *(Tubifex tubifex)*	48h EC50	Khangrot 1991
$BaSO_4$	32.0	Water flea *(Daphnia magna)*	48h EC50	Khangarot and Ray 1989
$BaCl_2$	25.0	Duckweed *(Lemna minor)*	96h EC50	Wang 1988
$BaCl_2$	14.5	Water flea *(Daphnia magna)*	48h EC50	Biesinger and Christensen 1972
	4.0		SCV	Suter and Tsao, 1996

BERYLLIUM

Beryllium (Be), an alkaline earth metal, is experimentally used as a missile propellant, in high-performance aerospace craft, the nuclear industry and other industrial purposes (Finch et al, 1990; Oehme, 1979). The emphasis of beryllium toxicity has recently shifted from purely industrial exposures to concern for general environmental contamination as a result of new uses. Be speciation is pH dependent, with Be concentration increasing as the pH declines (Jagoe et al., 1993).

Acute Toxicity. Morphological changes were observed (96h) in European perch *(Perca fluviatilis)* at concentrations as low as 0.01 mg/L (pH 5.5) including swelling of epithelial cell and reductions in microridges on cell surfaces. Fatal abnormalities such as the shortening of the secondary lamellae were observed at 0.05 mg/L, leading to a decrease in the surface area available for gas exchange. Be at pH 4.5 damaged epithelial cells causing a disruption in the ion and osmoregulatory systems (Jagoe et al, 1993). Be is more acidic and 100 times more toxic to guppies in soft water than hard water. In hard circumneutral water, guppies *(Lebistes reticulatis)* exhibited a 96h LC50 of 27.0 mg/L (Slonim, 1973) (Table 3).

Aquatic Mode of Action. Due to their similar chemical characteristics, it is believed that the toxicity mechanism of beryllium is similar to that of aluminum. Physiological processes of the gills such as ion regulation and gas exchange are affected, indicated by changes in chloride cell surface morphology and shortened secondary lamellae (Jagoe et al, 1993).

Water Quality Criteria. National ambient water quality criteria are not available. Calculated Tier II values are SAV- 35 and SCV-0.66 (Suter and Tsao, 1996).

Table 3. Acute toxicity of beryllium to aquatic organisms.

Compound	Conc[a] (mg/L)	Species	Effect	Reference
$Be(NO_3)_2$	20.00	Fathead minnow *(Pimephales promelas)*	96h LC50[b]	Tarzwell and Henderson 1960
$Be(NO_3)_2$	0.15	Fathead minnow *(Pimephales promelas)*	96h LC50[a]	Tarzwell and Henderson 1960
$BeCl_2$	>100.00	Fathead minnow *(Pimephales promelas)*	96h LC50	Ewell et al. 1986
$BeCl_2$	>100.00	Flatworm *(Dugesia tigrina)*	96h LC50	Ewell et al. 1986
$BeCl_2$	>100.00	Oligochaete *(Lumbriculus variegatus)*	96h LC50	Ewell et al. 1986
$BeCl_2$	>100.00	Ramshorn snail *(Heliosoma trivolvis)*	96h LC50	Ewell et al. 1986
$BeCl_2$	100.00	Aquatic sowbug *(Asellus intermedius)*	96h LC50	Ewell et al. 1986
$BeCl_2$	11.00	Fathead minnow *(Pimephales promelas)*	96h LC50[b]	Tarzwell and Henderson 1960
$BeCl_2$	1.90	Water flea *(Daphnia magna)*	24h LC50	LeBlanc 1980
$BeCl_2$	0.70	Scud *(Gammarus fasciatus)*	96h LC50	Ewell et al. 1986
$BeCl_2$	0.20	Fathead minnow *(Pimephales promelas)*	96h LC50[a]	Tarzwell and Henderson 1960
$BeCl_2$	0.05	Water flea *(Daphnia magna)*	96h LC50	Ewell et al. 1986
$BeSO_4$	259.70	Tubificid worm *(Tubiflex tubiflex)*	24h EC50[i]	Khangarot 1991

Compound	Conc[a] (mg/L)	Species	Effect	Reference
$BeSO_4$	102.50	Tubificid worm *(Tubiflex tubiflex)*	96h EC50[i]	Khangarot 1991
$BeSO_4$	55.90	Goldfish *(Carassius auratus)*	96h LC50	Cardwell et al. 1976a
$BeSO_4$	41.10	Flagfish *(Jordanella floridae)*	96h LC50	Cardwell et al. 1976a
$BeSO_4$	40.00	Nematode *(Caenorhabditis elegans)*	24h LC50	Williams and Dusenberry 1990
$BeSO_4$	31.50	Salamander *(Ambystoma opacum)*	24h LC50[h]	Slonim and Ray 1975
$BeSO_4$	23.70	Salamander *(Ambystoma opacum)*	24h LC50[s]	Slonim and Ray 1975
$BeSO_4$	23.60	Salamander *(Ambystoma maculatum)*	24h LC50[h]	Slonim and Ray 1975
$BeSO_4$	22.60	Salamander *(Ambystoma maculatum)*	96h LC50[h]	Slonim and Ray 1975
$BeSO_4$	22.00	Guppy *(Lebistis reticulatis)*	96h LC50[h]	Slonim and Slonim 1973
$BeSO_4$	17.70	Fathead minnow *(Pimephales promelas)*	96h LC50	Kimbal 1978
$BeSO_4$	12.00	Bluegill *(Lepomis macrochirus)*	96h LC50[h]	Tarzwell and Henderson 1960
$BeSO_4$	11.00	Fathead minnow *(Pimephales promelas)*	96h LC50[h]	Tarzwell and Henderson 1960
$BeSO_4$	8.94	Salamander *(Ambystoma maculatum)*	24h LC50[s]	Slonim and Ray 1975
$BeSO_4$	6.49	Salamander *(Ambystoma maculatum)*	96h LC50[s]	Slonim and Ray 1975
$BeSO_4$	4.64	Water flea *(Daphnia magna)*	24h EC50[i]	Khangarot and Ray 1989
$BeSO_4$	3.15	Salamander *(Ambystoma opacum)*	96h LC50[s]	Slonim and Ray 1975
$BeSO_4$	2.00	Guppy *(Lebistis reticulatis)*	24h LC50[s]	Slonim and Slonim 1973
$BeSO_4$	1.30	Bluegill *(Lepomis macrochirus)*	96h LC50[s]	Tarzwell and Henderson 1960
$BeSO_4$	0.20	Fathead minnow *(Pimephales promelas)*	96h LC50[s]	Tarzwell and Henderson 1960
$BeSO_4$	0.16	Guppy *(Lebistis reticulatis)*	96h LC50[s]	Slonim and Slonim 1973
$BeSO_4$	0.14	Nematode *(Caenorhabditis elegans)*	96h LC50	Williams and Dusenberry 1990
$BeSO_4$	0.07	Perch *(Perca fluviatilis)*	72h CV[p]	Jagoe et al. 1993
$BeSO_4$	0.07	Roach *(Rutilus rutilus)*	72h CV[p]	Jagoe et al. 1993
$BeSO_4$	0.005	Water flea *(Daphnia magna)*	24h CV[r]	Kimbal 1978

[a]-all concentrations are given as Be, not the compound
[h]- hard water(>400mg/L Ca)
[i]- immobilization
[p]- pH 5.5
[r]- reproduction
[s]- soft water (20-25 mg/L Ca)

BORON

Boron (B) is found in the earth's crust at an average concentration of 16 mg/kg (Oehme, 1979). Borax ($Na_2B_4O_7$), is used in soldering and welding to remove oxide film, for softening water, in soaps, and in glass, pottery, and enamels. Boron has medicinal properties as sodium borate and borax is used as a common cleaner (Dixon et al., 1976). Agricultural run off from the application of boric acid as an insecticide and non-selective herbicide acts as a non-point source that severly affects the ecology of wetlands (Sander et al., 1991; Smith and Anders, 1989). Boron is found in natural water supplies at levels lower than 1.0 mg/L, in soils of the Western U.S. at 10-300 mg/kg and is essential to plants (Smith and Anders, 1989). Boron can also be found in vegetables, fruits, cereals and breads (Valdes-Dapena and Arey, 1962).

Boron is released by weathering processes, existing in sediments as borosilicates, an inert compound with regard to metabolism of living animals (Butterwick et al., 1989). Boron speciation is dependent on water quality parameters such as boron concentration and pH (Maier and Knight, 1991). Boric acid, $B(OH)_3$ and $B(OH)^{4-}$ are the active forms of boron and are highly soluble and stable, however, it is not certain which form of the metal is most toxic. Unlike a number of other metals, boron toxicity is not affected by water hardness (Butterwick et al., 1989).

Acute Toxicity. Relatively little aquatic toxicity information is available for boron. The only standard data are LC50s and CVs for *Daphnia magna* exposed to boric acid in relatively hard water. Lewis and Valentine (1981) reported a 48h LC50 of 226 mg/L for *Daphnia magna.* The lethal threshold concentration was <200 mg/L of boron. Gersich (1984) reported a LC50 of 133 mg/L. Neonate stages of *D. magna* had a slightly higher 48h LC50 of 141 mg/L. Fourth instar, *Chironomus decorus* exhibited a 48h LC50 of 1376.0 mg/L B (Maier and Knight, 1991). Early life stages of rainbow trout *(Oncorhynchus mykiss)* are more sensitive than later stages with a LOEC of 0.1 mg/L B (Birge and Black, 1981). Hamilton and Buhl (1990) found that Chinook salmon *(Oncorhynchus tshawytscha)* have a higher LC50, 725.0 mg/L than do Coho salmon *(O. kisutch)*, 447.0 mg/L. The 24h LC50s for both species were greater than 1000.0mg/L, the highest concentration tested.

Chronic Toxicity. Gersich (1984) reported a CV of 9.33 mg/L for *D. magna* while Lewis and Valentine (1981) reported a slightly lower CV of 8.83 mg/L for the same species. Chronic exposures to sodium tetraborate significantly inhibited midge larvae growth at 20.0 mg/L (Maier and Knight, 1991). McKee and Wolf (1963) saw NOEC and LOEC values for *D. magna* to be 6.0 and 13.0 mg/L B.

Toxicity to Aquatic Plants. Root growth of *Myriophyllum spicatum* was inhibited by 50% after a 32d test at 40.3mg/L B as tetraborate salt (Butterwick et al., 1989).

Bioaccumulation. Boron can be bioaccumulated at higher concentrations but there is no biomagnification up the trophic levels (Ohlendorf et al., 1986). Coho salmon, *Oncorhynchus kisutch,* have a BCF of 22.4-2.7 (Thompson et al., 1976). Due to its polarity, boron does not bioaccumulate in fat tissue (Moseman, 1994). Instead, the target areas include the brain, spinal cord and liver (Whitworth et al. 1991). In the San Joaquin Valley of California an area of high boron run-off from agricultural fields, boron was found at concentrations of 371, 501 and 1860 mg/L in the wigeon grass, algae and grass seeds, respectively (Whitworth et al., 1991). Boron levels in aquatic vegetation seed have been as high as 3500.0 mg/kg, a concentration sufficient to adversely affect birds that feed upon it (Schuler, 1987).

Water Quality Criteria. No water quality criteria data are available. Calculated Tier II values are SAV- 29.65; SCV- 1.6 (Suter and Tsao, 1996).

CADMIUM

Cadmium (Cd) occurs predominately in the form of free divalent cations in most well oxygenated, low organic matter, fresh waters (EPA 1985-Cd). However, both particulate matter and dissolved organic matter can bind cadmium in biologically unavailable forms. There is no evidence that cadmium is a biologically essential or beneficial element (Eisler, 1985a). Cd toxicity is related to water hardness, with a reduction in toxicity associated with increased water hardness (EPA, 1985-Cd). Therefore, the cadmium toxicity values presented in Table 2 that are not from tests conducted in waters of moderate hardness are normalized to 100 mg/L using the slopes calculated by the EPA (1985-Cd).

Acute toxicity. See Table 4.

Chronic Toxicity. Fertilized eggs of the goldfish, leopard frog, and largemouth bass were placed in natural stream sediment spiked with cadmium (Francis et al., 1984) and maintained until four days posthatching, which resulted in a total exposure duration of six to seven days. Sediments with 1000 mg/kg cadmium were not toxic to goldfish or leopard frog but resulted in 25% mortality 4 days posthatching for largemouth bass. A sediment concentration of 100 mg/kg cadmium was not toxic to the largemouth bass. Organic matter content of the sediment was 2.3%.

Spiked sediment toxicity tests were performed using sediment from Steele's Run (organic carbon content of 2.3%), a stream in the Kentucky River drainage system. Treatment was of early-life-stage rainbow trout, in which the test was initiated at the early eyed-egg stage and continued through 10 days posthatching, giving an exposure period of 20 days. Sediment concentrations of between 2 and 13 mg/kg resulted in between 47 and 63% mortality relative to controls. A concentration of 121 mg/kg resulted in 89% mortality (Birge et al., 1979a).

Sauter et al. (1976; cited in Suter and Tsao, 1996) reported a CV of 0.0017 mg/L for fish and Chapman et al. (n.d; cited in Suter and Tsao, 1996) reported a CV of 0.00015 mg/L for Daphnids.

Bioaccumulation. Aquatic organisms are able to bioconcentrate Cd, although there is evidence that only the lower trophic levels can biomagnify this element.

Water Quality Criteria. NAWQ criteria values for Cd are 0.0039 and 0.0011mg/L for the acute and chronic toxicity of cadmium (Suter and Tsao, 1996).

Table 4. Toxicity of cadmium to aquatic organisms (EPA, 1985- Cd).

Concentration (mg/L)[a]		Effect
100 mg/L hardness	200 mg/L hardness	
24.6	72.8	Goldfish (*Carassius auratus*) LC50
18	18	Stonefly (Plecoptera) LC50[b]
17.7	38.7	Mayfly (*Ephemerella grandis*) LC50
17.3	37.8	Tubificid worm (*Rhyacodrilus montana*) LC50
16.8	36.7	Mosquitofish ((*Gambusia affinis*) LC50
16.5	36	White perch (*Morone americana*) LC50
15.1	33	Tubificid worm (*Stylodrilus heringlanus*) LC50
12.7	23.2	Bluegill (*Lepomis macrochirus*) LC50

Concentration (mg/L)[a]		Effect
100 mg/L hardness	200 mg/L hardness	
12.5	27.3	Channel catfish (*Ictalurus punctatus*) LC50
12.4	27	Tubificid worm (*Spirosperma nikolskyl*) LC50
10.9	23.8	Threespine stickleback (*Gasterosteus aculeatus*) LC50
10.4	22.8	Tubificid worm (*Varichaeta pacifica*) LC50
9.62	21.02	Tubificid worm (*Spirosperma ferox*) LC50
8.79	19.22	Tubificid worm (*Quistadrilus multisetosus*) LC50
8.79	19.22	Tubificid worm (*Tubifex tubifex*) LC50
8.3	18.15	Snail (*Amicola* sp.) LC50
7.8	17.5	Guppy (*Poecilla reticulata*) LC50
7.68	16.79	White sucker (*Catostomus commersoni*) LC50
7.43	16.24	Caddisfly (Trichoptera)LC50
6.86	12.85	Green sunfish (*Lepomis cyanellus*) LC50
6.59	14.41	Tubificid worm (*Branchiura sowerbyl*) LC50
6.31	13.79	Flagfish (*Jordanella floridae*) LC50
5.24	11.46	Northern squawfish (*Ptychochellus oregonensis*) LC50
5.05	11.04	Mayfly (*Paraleptophlebia praepedita*) LC50
4.67	10.21	Tubificid worm (*Limnodrilus hoffmelsterl*) LC50
3.71	8.12	Worm (*Nais* sp.) LC50
2.94	6.43	Pumpkinseed (*Lepomus gibbosus*) LC50
2.62	5.73	Midge (*Chironomus* sp.) LC50
1.61	3.52	American eel (*Anguilla rostrata*) LC50
0.875	1.913	Isopod (*Asellus bicrenata*) LC50
0.705	1.542	Crayfish (*Orconectes limosus*) LC50
0.484	1.06	Bryozoan (*Plumatella emarginata*) LC50
0.471	1.03	Common carp (*Cyprinus carpio*) LC50
0.448	0.979	Amphipod (*Hyalella azteca*) LC50
0.343	0.749	Snail (*Physa gyrina*) LC50
0.311	0.681	Bryozoan (*Pectinatella magnifica*) LC50
0.227	0.497	Snail (*Aplexa hypnorum*) LC50
0.216	0.472	Banded killifish (*Fundulus diaphanus*) LC50
0.181	0.397	Water flea (*Ceriodaphnia reticulata*) EC50
0.153	0.334	Amphipod (*Gammarus* sp.) LC50
0.132	0.288	Amphipod (*Gammarus pseudolimnaeus*) LC50
0.122	0.266	Water flea (*Daphnia pulex*) EC50
0.1	0.219	Cladoceran (*Simocephalus serralatus*) EC50
0.0935	0.2044	Isopod (*Lirceus alabamae*) LC50
0.0891	0.1948	Cladoceran (*Molina macrocopa*) EC50
0.072	0.1699	Fathead minnow (*Pimephales promelas*) LC50
0.0667	0.1459	Bryozoan (*Lophopodella carteri*) LC50
0.0281	0.0485	Bluegill (*Lepomis macrochirus*) CV
0.0266	0.0582	Water flea (*Daphnia magna*) EC50
0.0262	0.0452	Fathead minnow (*Pimephales promelas*) CV
0.0141	0.0243	Atlantic salmon (*Salmo salar*) CV
0.0141	0.0243	Smallmouth bass (*Micropterus dolomieui*) CV

Concentration (mg/L)[a]		Effect
100 mg/L hardness	200 mg/L hardness	
0.014	0.0242	Northern pike (*Esox lucius*) CV
0.014	0.0242	Lake trout (*Salvelinus namaycush*) CV
0.0135	0.0233	White sucker (*Catostomas commersoni*) CV
0.0129	0.0282	Coho salmon (*Oncorhynchus kisutch*) LC50
0.0127	0.0219	Brown trout (*Salmo trutta*) CV
0.0093	0.02032	Chinook salmon (*Oncorhynchus tshawytscha*) LC50
0.0092	0.01586	Flagfish (*Jordanella floridae*) CV
0.00834	0.01438	Snail (*Aplexa hypnorum*) CV
0.00784	0.01714	Rainbow trout (*Oncorhynchus mykiss*) LC50
0.00739	0.01274	Coho salmon (*Oncorhynchus kisutch*) CV
0.00678	0.01168	Cladoceran (*Ceriodaphnia reticulata*) CV
0.00464	0.008	Chinook salmon (*Oncorhynchus kisutch*) CV
0.00407	0.00701	Brook trout (*Salvelinus fontinalis*) CV
0.0039	0.0086	Acute NAWQC
0.00358	0.00782	Brown trout (*Salmo trutta*) LC50
0.0011	0.002	Chronic NAWQC
0.00033	0.00057	Cladoceran (*Molna macrocopa*) CV
0.000233	0.000401	Water flea (*Daphnia magna*) CV

[a] concentrations given as Cd, not the compound.
[b]- the stonefly acute test did not specify the hardness of the water

COBALT

Cobalt (Co), a hard, silvery white metal, is strategically important in the production of high-temperature alloys and permanent magnets (Brobst et al., 1973). Cobalt salts are utilized in the production of pigments and in paint dryers as catalysts (Lustigman et al., 1995). It is found in the earth's crust at an average concentration of 20 mg/kg. Cobalt is an essential element making up approximately one-half of the contents of vitamin B12, which is necessary in the prevention of pernicious anemia (Oehme, 1979). Comparatively little is known about the toxicity of cobalt.

Acute Toxicity. Acute toxicity values for cobalt ranged from 3.46 mg/L for fathead minnows to 139.32 mg/L for a tubificid worm (Table 5). Biesinger and Christensen (1972) reported 48h LC50s of 1.11 and 1.62 mg/L with and without food added, respectively. 16% reproductive impairment was seen at an exposure of 0.01 mg/L for 64h.

Chronic Toxicity. Chronic toxicity values (CVs) ranged from 5.1 mg/L for *D. magna* to 286.20 mg/L for the fathead minnow. Zebrafish embryos and larvae, *Brachydanio rerio,* were exposed to $CoCl_2$ for 16 days. NOECs of 0.06 and 3.84 mg/L were found for survival and hatching times, respectively (Dave and Xiu, 1991).

Toxicity to Aquatic Plants. 21d chronic tests using the unicellular alga, *Chlamydomonas reinhardtii,* exposed lethal toxic effects of cobalt (II) as $Co(NO_3)_2$ at 10-50 mg/L. Growth impairment starting at 10mg/L increased to the highest concentration tested (50 mg/L) and proved to be time and dose dependent. All cells at 50 mg/L were degraded and bleached, indicative of the inhibition of chlorophyll synthesis (Lustigman et al., 1995).

Aquatic Mode of Action. Mechanism for cobalt toxicity in aquatic plants may be linked to cobalt's competition with iron for active sites on the chlorophyll molecule (Lustigman et al., 1995).

Table 5. Toxicity of cobalt to aquatic organisms.

Conc. (mg/L)*	Species	Endpoint	Reference
286.20	Fathead minnow *(Pimephales promelas)*	CV	Kimball, 1978
139.32	Tubificid worm *(Tubifex tubifex)*	EC50	Khangarot, 1991
>100.00	Scud *(Gammarus fasciatus)*	LC50	Ewell et al., 1986
>100.00	Ramshorn snail *(Heliosoma trivolvis)*	LC50	Ewell et al., 1986
>100.00	Oligochaete *(Lumbriculus variegatus)*	LC50	Ewell et al., 1986
100.00	Aquatic sowbug *(Asellus intermedius)*	LC50	Ewell et al., 1986
25.00	Flatworm *(Dugesia tigrina)*	LC50	Ewell et al., 1986
23.00		SCV	Suter and Tsao, 1996
22.00	Fathead minnow *(Pimephales promelas)*	LC50	Ewell et al., 1986
17.59	Frog *(Rana hexadactyla)*	LC50	Khangarot et al., 1985
6.83	Water flea *(Daphnia magna)*	EC50	Kimball, 1978
5.15	Water flea *(Daphnia magna)*	EC50	Kimball, 1978

Conc. (mg/L)[a]	Species	Endpoint	Reference
5.10	Water flea *(Daphnia magna)*	CV	Kimball, 1978
3.75	Fathead minnow *(Pimephales promelas)*	LC50	Kimball, 1978
3.46	Fathead minnow *(Pimephales promelas)*	LC50	Kimball, 1978
1.48		SAV	Suter and Tsao, 1996

[a]- concentrations given as Co, not the compound

COPPER

Copper (Cu) occurs in natural waters primarily as the divalent cupric ion in free and complexed forms (EPA 1985-Cu). Copper is a minor nutrient for both plants and animals at low concentrations, but is toxic to aquatic life at concentrations only slightly higher. Concentrations of 0.001 to 0.010 mg/L are usually reported for unpolluted surface waters in the United States. Common copper salts, such as the sulfate, carbonate, cyanide, oxide, and sulfide are used as fungicides, as components of ceramics and pyrotechnics, for electroplating, and for numerous other industrial applications (ACGIH, 1986). The largest anthropogenic releases of copper to the environment result from mining operations, agriculture, solid waste, and sludge from sewage treatment plants.

Acute Toxicity. Toxicity of copper appears to be a function of calcium hardness and associated carbonate alkalinity. Therefore, the concentrations in Table 6 are corrected for hardness of 100 and 200 mg/L.

Bioaccumulation. Copper is not known to be appreciably bioaccumulated by fish, but some algae and bivalve molluscs do bioconcentrate or bioaccumulate copper by factors of over 1000 (EPA 1985-Cu).

Aquatic Mode of Action. The toxicity of copper to aquatic life is related primarily to activity of the cupric (Cu^{2+}) ion, and possibly to the hydroxy complexes. The cupric ion is highly reactive, forms moderate to strong complexes and precipitates with inorganic and organic constituents (e.g., carbonate, phosphate, amino acids), and is readily sorbed onto surfaces of suspended solids. The proportion of free cupric ion may be less than 1 percent in eutrophic waters where complexation predominates. These complexes appear to be much less toxic than free cupric ions, thus reducing toxicity. Hence, even dissolved copper measurements may overestimate copper exposure relative to laboratory test waters due to dissolved organic and inorganic ligands (EPA 1985-Cu; Benson et al., 1994).

Water Quality Criteria

The NAWQC for copper are fuctions of water hardness. The equations are $e^{(0.8545[\ln(\text{hardness})]-1.465)}$ for the chronic value and $e^{(0.9422[\ln(\text{hardness})]-1.464)}$ for the acute value (Suter and Tsao, 1996).

Table 6. Toxicity of copper to aquatic organisms (EPA-Cu, 1985).

Concentration (mg/L)[a]		Effect
100 mg/L hardness	200 mg/L hardness	
19.6757	37.8060	Stonefly (*Acroneuria lycorias*) LC50
11.2597	21.6351	White perch (*Morone americana*) LC50
8.2719	15.8940	American eel (*Anguilla rostrata*) LC50
3.8237	7.3471	Crayfish (*Procambarus clarkii*) LC50
3.6066	6.9299	Snail (*Campeloma decisum*) LC50
2.6843	5.1577	Crayfish (*Orconectes limosus*) LC50
1.7293	3.3228	Snail (*Amnicola*) LC50
1.6653	3.1999	Blacknose dace (*Rhinichthys atratulus*) LC50

Concentration (mg/L)[a]		Effect
100 mg/L hardness	200 mg/L hardness	
1.6653	3.1999	Rainbow darter (*Etheostoma caeruleum*) LC50
1.6134	3.1002	Creek chub (*Semotilus atromaculatus*) LC50
1.7434	2.9887	Bluegill (*Lepomis macrochirus*) LC50
1.5191	2.9189	Banded killifish (*Fundulus diaphanus*) LC50
1.3414	2.5774	Brown bullhead (*Ictalurus nebulosus*) LC50
1.3149	2.5264	Mozambique tilapia (*Tilapia mossambica*) LC50
1.2315	2.3662	Pumpkinseed (*Lepomis gibbosus*) LC50
0.6375	1.2250	Striped shiner (*Notropis chrysocephalus*) LC50
0.4663	0.8960	Worm (*Lumbriculus variegatus*) LC50
0.4492	0.8632	Sockeye salmon (*Oncorhynchus nerka*) LC50
0.4423	0.8499	Orangethroat darter (*Etheostoma spectabile*) LC50
0.3207	0.8254	Guppy (*Poecilia reticulata*) LC50
0.3789	0.7281	Midge (*Chironomus tentans*) LC50
0.3778	0.7258	Atlantic salmon (*Salmo salar*) LC50
0.3768	0.7240	Mosquitofish (*Gambusia affinis*) LC50
0.3217	0.6180	Northern squawfish (*Ptychocheilus oregonensis*) LC50
0.3193	0.6136	Snail (*Goniobasis livescens*) LC50
0.2644	0.6053	Fathead minnow (*Pimephales promelas*) LC50
0.3019	0.5800	Goldfish (*Carassius auratus*) LC50
0.3013	0.5789	Common carp (*Cyprinus carpio*) LC50
0.2594	0.4984	Bryozoan (*Pectinatella magnifica*) LC50
0.2556	0.4910	Chiselmouth (*Acrocheilus alutaceus*) LC50
0.2121	0.4076	Brook trout (*Salvelinus fontinalis*) LC50
0.1729	0.3323	Worm (*Nais sp.*) LC50
0.1509	0.2900	Central stoneroller (*Campostoma anomalum*) LC50
0.1387	0.2664	Bluntnose minnow (*Pimephales notatus*) LC50
0.1350	0.2594	Coho salmon (*Oncorhynchus kisutch*) LC50
0.1270	0.2441	Northern pike (*Esox lucius*) CV
0.1217	0.2234	Cutthroat trout (*Salmo clarki*) LC50
0.1080	0.2075	Snail (*Gyraulus circumstriatus*) LC50
0.1020	0.1960	Tubifed worm (*Limnodrilius hoffmeisteri*) LC50
0.0828	0.1590	Snail (*Physa integra*) LC50
0.0787	0.1457	Rainbow trout (*Oncorhynchus mykiss*) LC50
0.0712	0.1368	Bryozoan (*Lophodella carteri*) LC50
0.0712	0.1368	Bryozoan (*Plumatella emarginata*) LC50

Concentration (mg/L)[a]		Effect
100 mg/L hardness	200 mg/L hardness	
0.0690	0.1326	Snail (*Physa heterostropha*) LC50
0.0656	0.1260	Brook trout (*Salvelinus fontinalis*) CV
0.0649	0.1247	Brown trout (*Salmo trutta*) CV
0.0642	0.1234	Lake trout (*Salvelinus namaycush*) CV
0.0615	0.1182	Bluegill (*Lepomis macrochirus*) CV
0.0576	0.1108	Midge (*Chironomus*) LC50
0.0553	0.1063	Amphipod (*Gammarus pulex*) LC50
0.0645	0.0983	Chinook salmon (*Oncorhynchus tshawytscha*) LC50
0.0488	0.0939	Water flea (*Ceriodaphnia pulex*) EC50
0.0436	0.0900	Water flea (*Ceriodaphnia magna*) EC50
0.0439	0.0844	White sucker (*Catostomus commersoni*) CV
0.0434	0.0835	Fathead minnow (*Pimephales promelas*) CV
0.0424	0.0816	Amphipod (*Gammarus pseudolimnaeus*) LC50
0.0400	0.0769	Rainbow trout *(Oncorhynchus mykiss)* CV
0.0393	0.0756	Fathead minnow (*Pimephales promelas*) CV
0.0370	0.0710	Caddisfly (*Clistornia magnifica*) CV
0.0361	0.0693	Water flea(*Ceriodaphnia reticulata*) EC50
0.0296	0.0568	Chinook salmon (*Oncorhynchus tshawytscha*) CV
0.0273	0.0524	Brook trout (*Salvelinus fontinalis*) CV
0.0236	0.0454	Snail (*Campeloma decisum*) CV
0.0236	0.0454	Snail (*Physa integra*) CV
0.0039	0.0086	NAWQC Acute Value
0.0144	0.0277	Fathead minnow (*Pimephales promelas*) CV
0.0296	0.0249	Water flea(*Daphnia magna*) CV
0.0129	0.0247	Amphipod (*Gammarus pseudolimnaeus*) CV
0.0150	0.0243	Water flea (*Ceriodaphnia pulicaria*) EC50
0.0183	0.0219	Fathead minnow (*Pimephales promelas*) CV
0.0011	0.002	NAWQC Chronic Value
0.0098	0.0188	Brook trout (*Salvelinus fontinalis*) CV
0.0115	0.0097	Water flea(*Daphnia magna*) CV
0.0115	0.0097	Water flea(*Daphnia magna*) CV
0.0047	0.0091	Bluntnose minnow (*Pimephales notatus*) CV

[a]- concentrations are given as Cu, not the compound

IRON

Because iron (Fe) is the fourth most abundant element in the earth's crust, it commonly occurs at high concentrations in whole water analyses. Dissolved concentrations in water and soil are dependent upon redox conditions and pH. Fe typically occurs in water between 0.01 and 1.4 mg/L (Jorgensen et al., 1991; as cited in Gerhardt, 1994) with occurrence increasing in the presence of humic acids (Gerhardt, 1993). At lower concentrations, iron is an essential trace metal in both the plant and animal kingdoms because of its role in oxygen and energy transport. Iron occurs in the +1,+2 and +3 valence states and speciation from the +2 to the +3 state has been known to occur between pH 4.5 and 7. However, increased toxicity of iron at in acidic conditions may be a result of the photoreduction from +3 to the +2 state, or the destabilization of weaker iron complexes (Gerhardt, 1994). The most common dissolved inorganic form of iron is $Fe(OH)_2^+$ (Dave 1984). Toxicity of iron to aquatic organisms has received little attention because it is observed in unusual circumstances such as acid mine drainage or discharge of acidic metal working wastes.

Acute Toxicity. Iron is acutely toxic to freshwater fish and invertebrates at concentrations ranging from 0.300 mg/L to 2.0 mg/L (Train, 1979; cited in Dave, 1984). Survival of brown trout alevin (swim-up fry) and eyed-eggs was reduced at an average iron concentration of 5.170 mg/L (Geertz-Hansen and Mortensen 1983).

Uptake of and survival to iron was dose dependent in mayflys (*Leptophlebia marginata* L.) when exposed to 10-500 mg/L Fe. pH had little effect on the rate of uptake, but played an important role in survivability of the mayfly to Fe exposure. The 96h LC50 obtained during this study were 106.3 and 89.5 mg/L at pH 7 and 4.5, respectively. EC50s for escape behavior were 70 and 63.9 mg/L at pH 7 and 4.5, respectively (Gerhardt, 1994).

The common carp *(Cyprinus carpio)* had a LC50 of 1200 mg/L Fe as iron ammonium alum while the guppy had an LC50 of 1125 mg/L (Yarzhombek et al., 1991). Mullick and Konar (1991) found the 48h LC50 of a copepod *(Diaptomus forbesi)* to be 86.5 mg/L Fe as iron sulfate.

Chronic Toxicity. After 30d exposure to Fe at 10, 20 or 50 mg/L Fe as FeSO4, Gerhardt (1992a) observed decreased activity and food consumption by the mayfly *(Leptophlebia marginata)* at all concentrations tested (pH 4.5).

Reproduction of *Daphnia magna* was stimulated at concentrations up to 0.001 mg/L, and reproduction and survival were inhibited by iron at 0.158 mg/L and 0.256 mg/L, respectively (Dave, 1984). This is considerably lower than the 4.380 mg/L concentration causing 16% reproductive decrement in a 3 week test with *Daphnia magna* (Biesinger and Christensen, 1972). Dave argued that his result was more applicable to a situation in which "an acidic iron-containing waste water is discharged into a lake or a river" where it is neutralized, but Biesinger and Christensen's (1972) result "is probably more close to the steady-state situation in natural freshwater without any point source of iron."

Toxicity to Aquatic Plants. Wang (1986) found the 96h growth EC50 for duckweed *(Lemna minor)* to be 3.7 mg/L.

Bioaccumulation. Following acute (72h) exposure, the banded tilapia *(Tilapia sparrmanii)* exhibited a bioconcentration order of liver-ovary-heart-muscle-testis-brain, with the highest concentration being found in the liver (du Preez et al., 1993).

Aquatic Mode of Action. Excess Fe^{3+} in the liver of the banded tilapia *(Tilapia sparrmanii)* caused the excess formation of iron protein complexes such as hemoglobin, ferritin, and transferritin (Morgan, 1974; as cited in du Preez, et al., 1993). Fe stress is more detrimental to younger and female fish, as they invest more energy in reproduction than do males (Maltby and Naylor, 1991; as cited in Gerhardt, 1993).

LEAD

Lead (Pb), a comparatively rare metal, averages 16 mg/kg in the earth's crust, and is neither essential nor beneficial in living organisms (Eisler, 1988). Lead has adverse effects on survival, growth, reproduction, development, behavior, learning, and metabolism. In general, organic lead compounds are more toxic than inorganic compounds, biomagnification of lead is minimal, and younger organisms are more susceptible to lead toxicity (Eisler, 1988). Although lead occurs in a variety of forms in the aquatic environment, the relative toxicities of these forms are not well defined (EPA, 1985-Pb).

Acute Toxicity. Acute and chronic lead toxicity increases as hardness decreases (EPA, 1985-Pb). Therefore, the lead toxicities values to aquatic life, listed in Table 1, are normalized to 100 and 200 mg/L hardness using the slopes calculated by the EPA (1985-Pb). Acute toxicities of lead, normalized to 100 mg/L, range from 0.3446 to 570.201 mg/L and acute toxicities, normalized to 200 mg/L, range from 0.8328 to 1377.968 mg/L. Biesinger and Christensen (1972) reported a 48-hr LC50 of 0.45 mg/L without food added for the toxicity of lead to *Daphnia magna* (Table 7).

Chronic Toxicity. Chronic toxicities, normalized to 100 mg/L, range from 0.0167 to 0.3874 mg/L and chronic toxicities, normalized to 200 mg/L, range from 0.0405 to 0.9362 mg/L. In general, invertebrates are more sensitive to lead than fish. Biesinger and Christensen (1972) reported a 3-week CV of 0.030 mg/L with food added for the toxicity of lead to *Daphnia magna* which caused 16% reproductive impairment.

Toxicity to Aquatic Plants. Monahan (1976; as cited in EPA, 1985-Pb) exposed three species of alga to various concentrations of lead chloride. 0.5 mg/L Pb proved to inhibit growth by 53, 35 and 52% in *Chlorella* sp., *Scenedesmus* sp., and *Selenastrum* sp., respectively. 32d chronic exposure to Eurasian watermilfoil *(Myriophyllum spicatum)*, yielded an EC50 for root growth of 363 mg/L (Stanley, 1974; as cited in EPA, 1985-Pb). Investigating the effects of lead shot on rooted aquatic plants, Behan et al. (1979) found that the bioavailability of powdered lead is much higher than that of lead shot. Depuration of accumulated lead is comparatively rapid; 10% of the Pb absorbed during the first hour of exposure by *Elodea canadensis* remained in the shoot tissue 14d after transfer to clean water (Everard and Denny, 1985; as cited in Eisler, 1988).

Bioaccumulation. Biomagnification of lead does not occur in aquatic food chains as evidenced by its relatively high concentrations in aquatic plants and invertebrates and low concentrations in fish (Eisler, 1988). Bioconcentration factors range from 1700 for a snail *(Lymnaea palustris)* to 42 for the brook trout *(Salvelinus fontinalis)* (Borgman et al., 1978; Holcombe et al., 1976).

Water Quality Criteria. The acute and chronic NAWQ criteria for lead are 0.082 and 0.0032 mg/L at a hardness of 100 mg/L as $CaCO_3$ (EPA, 1985- Pb).

Table 7. Toxicity of lead to aquatic organisms (EPA 1985- Pb).

Concentration (mg/L)		Effect
100 mg hardness	200 mg hardness	
570.201	1377.968	Midge (*Tanytarsus dissimilis*) LC50
244.399	590.623	Goldfish (*Carassius auratus*) LC50

Concentration (mg/L)		Effect
100 mg hardness	200 mg hardness	
159.829	386.249	Guppy (*Poecilia reticulata*) LC50
71.706	202.114	Fathead minnow (*Pimephales promelas*) LC50
105.421	212.455	Bluegill (*Lepomis macrochirus*) LC50
13.610	75.668	Rainbow trout (*Oncorhynchus mykiss*) LC50
11.659	28.176	Brook trout (*Salvelinus fontinalis*) LC50
2.514	6.076	Snail (*Aplexa hypnorum*) LC50
0.9087	1.8441	Water flea (*Daphnia magna*) EC50
0.3874	0.9362	Rainbow trout (*Oncorhynchus mykiss*) CV
0.3446	0.8328	Amphipod (*Gammarus pseudolimnaeus*) LC50
0.2363	0.5709	Brook trout (*Salvelinus fontinalis*) CV
0.1134	0.5696	Water flea (*Daphnia magna*) CV
0.0562	0.2821	Water flea (*Daphnia magna*) CV
0.0491	0.2464	Water flea (*Daphnia magna*) CV
0.0954	0.2307	Rainbow trout (*Oncorhynchus mykiss*) CV
0.0167	0.0405	Snail (*Lymnaea palustris*) CV
0.082	0.197	NAWQC acute value
0.0032	0.0077	NAWQC chronic value

LITHIUM

The concentration of lithium (Li)found in the earth's crust is 30 mg/kg. Metallic lithium does not occur in nature, it occurs as salts and complexes. Lithium is not considered a heavy metal or an essential element (Oehme, 1979).

Acute Toxicity. The striped bass 96 hr LC50 in a static test of lithium was >105 mg/L (Dwyer et al., 1992). Survival of the striped bass increased as the hardness of the water was increased. Recent studies conducted at Oak Ridge National Laboratory have revealed that the toxicity of lithium decreases as the concentration of sodium increases (Kszos, 1996). Survival of *Ceriodaphnia dubia* exposed to lithium concentrations ranging from 1-4 mg/L increased as sodium concentrations were increased. The feeding rate for *Elimia clavaeformis* was reduced by 25% at 0.11 mg/L, the growth of *Pimephales promelas* was reduced by 25% at 0.42 mg/L, and the reproduction of *Ceriodaphnia dubia* was reduced by 25% at 0.46 mg/L in 7 day tests. Studies of three species of fish by Hamilton (1995) showed lithium to be more toxic to fry than juveniles (Table 8). Lithium was found to have an EC50 (50% immobilization response) for tubificid worms (*Tubifex tubifex)* of 44.77 mg/L at the 24 hr, 11.22 mg/L at the 48 hr, and 9.34 mg/L at the 96 hr (Khangarot, 1991).

Toxicity to Aquatic Plants. Lithium as LiCl gradually decreased cell growth of the alga, *Chlamydomonas reinhardii* between 13.9 and 138.8 mg/L over a 6 day period (Gamboa et al., 1985). LiCl placed in the alga media caused loss of cell mobility and production of large amounts of extracellular mucus. This toxicity is due to the free cation.

Aquatic Mode of Action. The mode of action of lithium is unclear. However, lithium may interfere with or substitute for sodium, potassium, calcium, and magnesium (Klemfuss and Greene, 1991).

Table 8. Toxicity of lithium to aquatic organisms.

Conc. (mg/L)	Effect	Reference
186.00	Razorback sucker (2.0g-juvenile)LC50	Hamilton, 1995
138.80	Algae (*Chlamydomonas reinhardii*)75% growth inhibition	Gamboa et al., 1985
65.00	Bonytail (2.6g-juvenile)LC50	Hamilton, 1995
62.00	Bonytail (1.1g-juvenile) LC50	Hamilton, 1995
53.00	Razorback sucker (0.9g-juvenile) LC50	Hamilton, 1995
44.77	Tubificid worm (*Tubifex tubifex)*24hr EC50	Khangarot, 1991
41.00	Colorado squawfish (1.7g-juvenile) LC50	Hamilton, 1995
28.00	Colorado squawfish (0.4-1.1g-juvenile) LC50	Hamilton, 1995
25.00	Razorback sucker (swimup fry) LC50	Hamilton, 1995
2.00	Bonytail (swimup fry) LC50	Hamilton, 1995
17.00	Colorado squawfish (swimup fry) LC50	Hamilton, 1994

Conc. (mg/L)	Effect	Reference
13.90	Algae (*Chlamydomonas reinhardii*) 25% growth inhibition	Gamboa et al., 1985
11.22	Tubificid worm (*Tubifex tubifex*) 48hr EC50	Khangarot, 1991
9.34	Tubificid worm (*Tubifex tubifex*) 96hr EC50	Khangarot, 1991

[a]Concentration causing 25% reduction in test endpoints compared to control
[b]Nominal concentration
[c]Measured concentration

MANGANESE

Manganese (Mn) makes up about 0.10% of the earth's crust and is the 12th most abundant element (NAS, 1980). In soil, natural levels of manganese range from 0.6-0.9 mg/kg and its solubility increases with decreasing pH. In surface water, Mn is present at concentrations ranging from 0.001-0.04 mg/L (Rouleau et al., 1995). Manganese oxides and peroxides are used in industry as oxidizers, and elemental Mn is used for manufacturing metal alloys to increase hardness and corrosion resistance. Increasingly, Mn as a Mn carbonyl compound, is being utilized as an anti-knocking agent in engines and is released into the air as Mn_3O_4 following combustion (Brault et al., 1994). Manganese is also present in the air and water discharges from mining and smelting activities (Saric 1986). In living systems, manganese is an essential element that is found most often in the +2 valence state. There is evidence that manganese occurs in surface waters both in suspension in the quadrivalent state and in the trivalent state in a relatively stable, soluble complex (APHA,1989). Manganese is one of the first metals to increase in concentration in acidified waters (Harvey 1983).

Acute Toxicity. Mn is not considered to be severe, acute threat to fish, as 96h LC50 values range much higher than concentrations that are found in surface waters. The 96h LC50 is 3,230 mg/L for the tropical perch *(Colisa fasciatus)* (Nath and Kumar, 1987), 1679.0 mg/L for *Oreochromis mossambicus* (Seymore et al., 1993), and 130.0 mg/L for the logfin dace *(Agosia chrysogaster)* (Lewis, 1978).

Acute and chronic toxicity tests using fathead minnows and *Daphnia magna* were conducted in relatively hard water. Acute toxicity values for manganese ranged from 19.4 mg/L for *D. magna* to 33.80 mg/L for fathead minnow (Kimball, 1978). Manganese toxicity was increased by the presence of food during the *D. magna* acute toxicity tests. Biesinger and Christensen (1972) reported an LC50 of 9.80 mg/L for *D. magna* without food added (Table 9).

Chronic Toxicity. Biesinger and Christensen (1972) reported an EC50 value for reproductive impairment of 5.2 mg/L and a 3-week LC50 of 5.7 mg/L. The CV of 4.10 mg/L based on a 3-week toxicity test resulted in 16% reproductive impairment of *D. magna.*

After a 30d exposure to Mn, brown trout showed a decrease in body calcium concentrations and impaired development in the two highest concentrations (0.36 and 1.08 mg/L) tested (Reader et al., 1988). The CV for this assay was calculated at 0.21 mg/L.

Bioaccumulation. Body concentrations of Mn in aquatic organisms is not dependent on the ambient concentration of the metal (Bendell-Young and Harvey, 1986). In young trout, Mn has been known to concentrate in newly forming fibrous or cartilaginous bone (Hibiya 1982), while in older fish, Mn targets the liver and gills (Rouleau et al., 1995). Studies on the bioaccumulation of Mn have found bioconcentration factors for brown trout, fathead minnow, and yellow perch to be 17.8, 22.6 and 12.0, respectively (Rouleau et al., 1995; Kwasnik et al., 1978; Kerns and Vetter, 1982).

Benthic invertebrates appear to play an important role in the transfer of Mn to fish. 70% of the whole body concentrations of Mn was present in the gut contents of *Tipula* (spp.), a detritus feeding aquatic insect (Elwood et al., 1976).

Aquatic Mode of Action. Manganese uptake to the brain occurs via the olfactory system which by its nature, enables the quick deposition of the metal in the olfactory bulb of the brain

(Rouleau et al., 1995). Body deposition occurs via the circulatory system targeting the liver, kidney, muscle and inorganic portions of the bone (Bendell-Young and Harvey, 1986).

Once transfered to the organs, manganese impairs calcium transport. Fish from lakes with high levels of manganese exhibit symptoms of impaired transport of calcium during oogenesis and altered calcium deposition in the skeleton (Beamish et al., 1975; Fraser and Harvey, 1982). Ca^{2+}-ATPase activity on the gill is inhibited and both net uptake and deposition of calcium were impaired by manganese (Reader et al., 1988).

Table 9. Toxicity of manganese to aquatic organisms.

Conc.[a] (mg/L)	Species	Effect	Reference
333000.0	aquatic sowbug *(Asellus aquaticus)*	96h EC50[i]	Martin and Holdich, 1986.
77100.0	aquatic sowbug *(Asellus aquaticus)*	48h EC50[i]	Martin and Holdich, 1986.
51000.0	crayfish *(Orconectes limosus)*	96h LC50	Boutet and Chaisemartin, 1973.
38700.0	rotifer *(Brachionus calyciflorus)*	24h LC50	Couillard et al., 1989.
28000.0	crayfish *(Austropotamobius pallipes)*	96h LC50	Boutet and Chaisemartin, 1973.
16620.0	frog *(Microhyla ornata)*	24h LC50	Rao and Madhyastha, 1987.
16030.0	frog *(Microhyla ornata)*	48h LC50	Rao and Madhyastha, 1987.
3230.0	tropical perch *(Colisa fasciatus)*	96h LC50	Nath and Kumar, 1987.
1679.0	*(Oreochromis mossambicus)*	96h LC50	Seymore et al., 1993
130.0	logfin dace *(Agosia chrysogaster)*	96h LC50	Lewis, 1978.
9.8	water flea *(Daphnia magna)*	LC50	Biesinger and Christensen, 1972.

[a]- concentrations given as Mn, not the compound
[i]- immobilization

MERCURY

Mercury (Hg) has no known biological function and is toxic to fish and wildlife. It is a mutagen and carcinogen that adversely affects the central nervous, renal, and reproductive systems of wildlife. Hg occurs in the environment as elemental mercury, Hg_2(II) and Hg(II), the latter of which is naturally oxidized from elemental mercury (Eisler, 1987). Mercury in ambient waters commonly occurs as mercury (II) or methylmercury. Mercury (II) can be methylated by both aerobic and anaerobic bacteria in the slime coat, liver, and intestines of fish, but methylation apparently does not occur in other tissues or in plants (EPA, 1985-Hg). From a toxicological standpoint, methylmercury (MeHg) poses a greater threat to biota due to its high stability and the ease with which it penetrates membranes in living organisms. Hg(II), however, is more prevalent in aquatic systems, bound up and unavailable in sediment layers. Biota bioconcentrate mercury compounds which can be further biomagnified through food chains (Wren, 1986). High concentrations of mercury in water are often associated with low alkalinity lakes and newly created bodies of water (Weiner and Stokes, 1990). Alkalinity, ascorbic acid, chloride, dissolved oxygen, hardness, organic complexing agents, pH, sediment, and temperature probably affect the acute and chronic toxicity and bioaccumulation of the various forms of mercury.

Anthropogenic sources of Hg include the combustion of fossil fuels, metal mining and processing plants, chloralkali plants, and disposal of batteries and fluorescent lamps (NAS 1978, and Das et al., 1982; as cited in Eisler, 1987).

Acute Toxicity. Acute toxicity values for mercuric chloride range from 0.001 mg/L for the toad, *Gastroqhyryne carolinensis* (Birge et al., 1979b) to 2.00 mg/L for the caddisfly, *Hydropsyche betteni* (EPA, 1985-Hg) (Table 10). Acute toxicty values for methylmercury include 96h LC50s of 0.065 and 0.024 mg/L for brook trout *(Salvelinus fontinalis)* (McKim et al., 1976) and rainbow trout *(Oncorhynchus mykiss)* (EPA, 1980) (Table 11).

As reported by Armstrong (1979; as cited in Eisler, 1987) symptoms of acute mercury poisoning include, "flaring of gill covers, increased frequency of respiratory movements, loss of equilibrium, and sluggishness."

Chronic Toxicity. Fathead minnows *(Pimephales promelas)* were exposed to 0.00026-0.00369 mg/L $HgCl_2$ for 41 weeks. Reproductive inhibition, including a decrease in egg production, occurred at all concentrations tested while spawning ceased at 0.001 mg/L and above. Significant growth retardation of males occurred at 0.00369 mg/L. During the second part of the assay, a 60d test, survival of the minnows was significantly reduced at 0.00451 mg/L. After 30d of testing, growth retardation was evident at and above 0.00127 mg/L. The 7d LC50 was calculated at 0.074 mg/L Hg (Snarski and Olson, 1982).

When comparing three mercury compounds, Biesinger et al., 1982 found that MeHg was more fatal to *Daphnia magna* than $HgCl_2$ and phenyl mercuric acetate (PMA) following a 3 week exposureii. At 0.004 mg/L MeHg, survival was 0% following an 8d exposure. PMA decreased survival by 26% at 0.005 mg/L and by 97% at 0.01 mg/L. $HgCl_2$ proved 100% fatal at 0.0136 mg/L and 40% fatal at 0.0068 mg/L.

Dave and Xiu (1991) ran 16d tests on the embryos and larvae of the zebrafish *(Brachydanio rerio)* exposing the fish to 0.001-0.512 mg/L Hg as HgCl2. At 0.032, hatching was completely inhibited and the CV was calculated at 0.002 mg/L. The 3-week CV for the toxicity of mercury to

D. magna is 0.0034 mg/L resulting in 16% reproductive impairment (Biesinger and Christensen, 1972) (Table 10).

As reported by Armstrong (1979; as cited in Eisler, 1987) symptoms of chronic mercury exposure in fish include, "emaciation (due to appetite loss), brain lesions, cataracts, diminished response to change in light intensity, inability to capture food, abnormal motor coordination, and various erratic behaviors."

Toxicity to Aquatic Plants. Toxicity values for mercuric chloride range from a 32d EC50 (root weight) of 3.4 mg/L for eurasian milfoil (Stanley, 1974) to an acute EC50 for the alga *(Anabaena flosaque)* of 0.053 mg/L (Thomas and Montes, 1978) (Table 1). *Pistia stratiotes* L. were exposed to 0.05-20.0 mg/L Hg as $HgCl_2$ for 7d. At 20.0 mg/L all plants died after 2d. No other deaths were reported in the remaining test groups (De et al., 1985).

Bioaccumulation. Uptake of MeHg by aquatic organisms may range from 8.5 to 16 times greater than that of Hg(II) (Olson et al., 1975; as cited in Snarski and Olson, 1982). Uptake and accumulation of mercury compounds by *Daphnia magna* was measured by Biesinger et al. (1982). MeHg yielded the highest tissue concentration of 184.5 mg/kg upon exposure to 0.00026 mg/L and $HgCl_2$ yielded a tissue concentration of 23.28 mg/kg upon exposure to 0.0027 mg/L.

Snarski and Olson (1982) exposed fathead minnows to 0.00031- 0.00451 mg/L Hg as $HgCl_2$. Whole body concentrations of mercury reflected water concentration ranging from 0.8 mg/kg at the lowest concentration tested to 4.18 mg/kg at the highest concentration tested.

Maximum accumulation of Hg(II) in *Pistia stratiotes* L. occurred in the roots and shoots during first day of exposure to 0.05-20.0 mg/L Hg(II) (De et al., 1985).

Hg has a biological half life in fish of 2-3 years. Depuration of mercury from aquatic organisms is considered extremely slow, and decreases in body concentration may be primarily due to dilution from tissue growth and development (EPA, 1985-Hg).

Aquatic Mode of Action. Mercury binds with sulfhydrl groups on proteins resulting in numerous sites and modes of action. Probably the most important is inhibition of cell division.

Water Quality Criteria. The NAWQ criteria for Hg(II) is 0.00244 mg/L and the final chronic value is 0.00130 mg/L (EPA, 1985- Hg). Calculated Tier II values for methylmercury are SAV- 0.000099 mg/L; SCV- 0.0000028 mg/L (Suter and Tsao, 1996).

Table 10. Toxicity of mercuric chloride to aquatic organisms.

Conc. (mg/L)[a]	Species	Effect[b]	Reference
3.400	eurasian milfoil *(Myrophyllum spicatum)*	32d EC50	Stanley, 1974
2.000	caddisfly *(Hydropsyche betteni)*	LC50	EPA, 1985-Hg
2.000	mayfly *(Ephemerella subvaria)*	LC50	EPA, 1985-Hg
2.000	stonefly *(Acroneuria lycorias)*	LC50	EPA, 1985-Hg
1.400	indian food fish *(Channa gachua)*	96h LC50	Hanumante and Kulkarni, 1979.

Conc. (mg/L)[a]	Species	Effect[b]	Reference
1.030	alga *(Chlorella vulgaris)*	33d EC50	Rosko and Rachlin, 1977
1.000	mozambique tilapia *(Tilapia mossambica)*	LC50	EPA, 1985-Hg
0.500	tubificid worm *(Spirosperma nikolskyi)*	LC50	EPA, 1985-Hg
0.440	fish *(Notopterus notopterus)*	96h LC50	Verma and Tonk, 1983
0.370	snail *(Aplexa hypnorum)*	96h LC50	Holcombe et al., 1983
0.330	tubificid worm *(Spirosperma ferox)*	LC50	EPA, 1985-Hg
0.250	tubificid worm *(Quistadrilus multisetosus)*	LC50	EPA, 1985-Hg
0.240	coho salmon *(Oncorhynchus kisutch)*	96h LC50	Lorz, 1978
0.240	tubificid worm *(Rhyacodrilus montana)*	LC50	EPA, 1985-Hg
0.180	tubificid worm *(Limnodrilus hoffmeisteri)*	LC50	EPA, 1985-Hg
0.168	fathead minnow *(Pimephales promelas)*	96h LC50	Snarski and Olson, 1982
0.160	bluegill *(Lepomis macrochirus)*	96h LC50	Holcombe et al., 1983
0.140	tubificid worm *(Stylodrilus heringianus)*	LC50	EPA- Hg, 1985
0.140	tubificid worm *(Tubifex tubifex)*	LC50	EPA- Hg, 1985
0.108	salamander *(Ambystoma opacum)*	96h LC50	Birge et al., 1979b
0.100	tubificid worm *(Varichaeta pacifica)*	LC50	EPA, 1985-Hg
0.080	tubificid worm *(Branchiura sowerbyi)*	LC50	EPA, 1985-Hg
0.074	fathead minnow *(Pimephales promelas)*	7d LC50	Snarski and Olson, 1982
0.063	frog *(Rana catesbeiana)*	96h LC50	McCrary, 1995
0.053	alga *(Anabuena flosaquae)*	EC50	Thomas and Montes, 1978
0.053	mosquitofish *(Gambusia affinis)*	96h LC50	McCrary, 1995
0.050	crayfish *(Orconectes limosus)*	LC50	EPA, 1985-Hg
0.044	aquatic oligochaete *(Lumbriculus variegatus)*	96h LC50	McCrary, 1995
0.030	guppy *(Poecilla reticulata)*	LC50	EPA, 1985-Hg
0.020	crayfish *(Faxonella clypeatus)*	LC50	EPA, 1985-Hg
0.017	fish *(Notemigonus crysoleucas)*	96h LC50	McCrary, 1995
0.015	frog *(Rana clamitans)*	96h LC50	McCrary, 1995
0.010	cricket frog *(Acris sp.)*	96h LC50	Birge et al., 1979
0.010	scud *(Gammarus pseudolimnaeus)*	96h LC50	EPA, 1980
0.007	leopard frog *(Rana pipens)*	96h LC50	Birge et al., 1979b
0.007	frog *(Rana sphenocephala)*	96h LC50	McCrary, 1995
0.005	water flea *(Daphnia magna)*	96h LC50	EPA, 1980

Conc. (mg/L)[a]	Species	Effect[b]	Reference
0.0034	water flea *(Daphnia magna)*	CV	Biesinger and Chistensen, 1972
0.003	water flea *(Daphnia magna)*	EC50	EPA, 1985-Hg
0.002	acute NAWQC		EPA, 1985-Hg
0.002	treefrog *(Hyla spp.)*	96h LC50	Birge et al., 1979b
0.002	water flea *(Daphnia pulex)*	EC50	EPA- Hg, 1985
0.002	crayfish *(Orconectes limosus)*	30d LC50	EPA, 1980
0.002	zebrafish *(Brachydanio rerio)*	CV	Dave and Xiu, 1991
0.001	final chronic value		EPA, 1985-Hg
0.001	toad *(Gastrophyryne carolinensis)*	96h LC50	Birge et al., 1979b
0.00023	fathead minnow *(Pimephales promelas)*	CV	EPA, 1985-Hg

[a]- concentrations given as Hg(II) not the compound
[b]- all endpoints are considered acute, unless otherwise noted

Table 11. Toxicity of methylmercury to aquatic organisms.

Conc. (mg/L)[a]	Species	Endpoint	References
0.50000	flatworm *(Dugesia dorotocephala)*	5d LC100	Best et al., 1981
0.06500	brook trout *(Salvelinus fontinalis)*	96h LC50	EPA, 1980
0.02400	rainbow trout *(Oncorhynchus mykiss)*	96h LC50	EPA, 1980
0.00600	alga *(Anabaena flosaquae)*	EC50	Thomas and Montes, 1978
0.00052	brook trout *(Salvelinus fontinalis)*	CV	McKim et al., 1976
0.00004	water flea *(Daphnia magna)*	CV	Biesinger et al., 1982

[a]- concentrations given as MeHg

NICKEL

Nickel is a naturally occuring element that may exist in various mineral forms. It forms 0.008% of the earth's crust (NAS, 1980). Soil and sediment are the primary receptacles for nickel, but mobilization may occur depending on physico-chemical characteristics of the soil (ATSDR, 1988; USAF, 1990). Nickel is used in a wide variety of applications including metallurgical processes and electrical components, such as batteries (ATSDR, 1988; USAF, 1990). There is some evidence that nickel may be an essential trace element for mammals. Nickel occurs in nature in the nonionic and divalent states; other valence states occur very infrequently (Mastromatteo, 1986). Although nickel can exist in several oxidation states, the divalent cation state predominates and is generally considered the most toxic form (EPA 1986-Ni). As with many metals the toxicity of nickel increases as hardness decreases. Fish and invertebrates have approximately the same range of sensitivity.

Acute Toxicity. Acute toxicities of nickel to aquatic life, normalized to 100 and 200 mg/L of hardness, are presented in Table 12. Acute toxicities, normalized to 100 mg/L, range from 2.5 to 77.7 mg/L and while acute toxicities normalized to 200 mg/L range from 5.7 to 139.7 mg/L. Biesinger and Christensen (1972) reported 48-hr LC50 values for *D. magna* of 1.120 and 0.510 mg/L with and without food, respectively.

Chronic Toxicity. The chronic toxicity of nickel to aquatic life, normalized to 100 mg/L, range from 0.0106 to 0.502 mg/L while chronic toxicities normalized to 200 mg/L, range from 0.398 to 0.746 mg/L. In general, invertebrates are more sensitive to nickel than fish. Biesinger and Christensen (1972) reported a 3-week CV of 0.030 mg/L which caused 16% reproductive impairment in *D. magna*.

Table 12. Toxicity of nickel to aquatic organisms (EPA 1986-Ni).

Concentration (mg/L)		Effect
100 mg/L hardness	200 mg/L hardness	
77.7	139.7	banded killifish (*Fundulus diaphanus*) LC50
72.7	130.7	stonefly (*Acroneuria lycorias*) LC50
54.3	97.6	caddisfly LC50
38.3	68.9	goldfish (*Carassius auratus*) LC50
38.1	68.5	damselfly LC50
25.3	45.6	Worm (*Nais sp.*) LC50
24.1	43.2	rainbow trout (*Oncorhyncus mykiss*) LC50
23.4	42	amphipod (*Gammarus* sp.) LC50
23.3	41.8	white perch (*Morone americana*) LC50
23	41.3	snail (*Amnicola sp.*) LC50
21.9	39.4	American eel (*Anguilla rostrata*) LC50
19.4	31.4	bluegill (*Lepomis macrochirus*) LC50
17.6	31.7	common carp (*Cyprinus carpio*) LC50
17.4	31.2	guppy (*Poecilla reticulata*) LC50
14.3	25.3	fathead minnow (*Pimephales promelas*) LC50
13.6	24.4	pumpkinseed (*Lepomis gibbosus*) LC50
12.2	25.2	striped bass (*Morone saxatillis*) LC50
8.33	15	Mayfly (*Ephemerella subvaria*) LC50
7.75	13.9	rock bass (*Ambioplites rupestris*) LC50
3.67	6.6	*Daphnia pulicaria* EC50

Concentration (mg/L)		Effect
100 mg/L hardness	200 mg/L hardness	
2.5	5.7	*Daphnia magna* EC50
1.42	2.55	acute NAWQC
0.502	0.746	fathead minnow (*Pimephales promelas*) CV
0.231	0.415	Caddisfly (*Clistoronia magnifica*) CV
0.162	0.291	rainbow trout (*Oncorhynchus mykiss*) CV
0.158	0.283	chronic NAWQC
0.0809	0.398	*Daphnia magna* CV
0.0106		*Ceriodaphnia dubia* CV[a]

[a] Seven day test at 117 mg/L hardness from Kszos et al. (1992).

SELENIUM

Selenium (Se), is an essential nutrient for some plants and animals when present in trace amounts. However, at levels currently present in the environment, Se poses a significant toxic risk. Anthropogenic sources include the combustion of fossil fuels, municipal wastes, irrigation run-off and industrial effluents. Lechate from seleniferous soils also contributes to the presence of Se in the environment (Eisler, 1985b). Selenium has a combination of attributes which make it an unusual pollutant (EPA, 1987). These attributes include, but are not limited to, the following: it is an essential trace nutrient; it can occur in three oxidation states and be reduced or oxidized by various organisms; it is a metalloid with physicochemical properties similar to sulfur, which may reduce the toxicity of selenium or be replaced by selenium in biologically important compounds; it can reduce the toxicity of several heavy metals and have varying effects on cadmium and mercury toxicity; both water and food are important exposure pathways for aquatic biota; and there are substantial natural and anthropogenic releases to water. The two oxidation states (Se(IV) and Se(VI)) for which the most toxicity data exist are discussed separately. Plants have the ability to convert inorganic selenium to organic selenium compounds, thereby increasing their biological availability (Lo and Sandi, 1980).

Acute Toxicity. Acute toxicity values for Se(IV) are available for 23 freshwater fish and invertebrate species in 22 genera and range from 0.304 mg/L for the amphipod *Hyalella azteca* to 203.0 mg/L for the leech *Nephelopsis obscura.* The two most sensitive and resistant species were invertebrates. The species mean acute values were (0.8555 mg/L) for *Daphnia magna* and (1.601 mg/L) for the fathead minnow (EPA, 1987).

Acute toxicity values for Se(VI) are available for 12 freshwater animal species and range from 0.06538 mg/L for the amphipod *Gammarus pseudolimnaeus* to 442.0 mg/L for the leech *Nephelopsis obscura.* The species mean acute values were (1.450 mg/L) for *Daphnia magna* and (5.5 mg/L) for the fathead minnow (EPA, 1987) (Tables 13,14).

Chronic Toxicity. Chronic values for Se(IV) ranged from >0.047 mg/L for the rainbow trout *(Onchorhychus mykiss)* to 0.6928 mg/L for *D. magna.* Chronic values for Se(VI) ranged from 0.5655 mg/L for the fathead minnow *(Pimephales promelas)* to 2.891 mg/L for the rainbow trout *(Onchorhychus mykiss). Daphnia magna* had a chronic value of 1.99 mg/L (EPA, 1987) (Table 13, 14).

Toxicity to Aquatic Plants. Kumar and Prakash (1971) found the 96h LC50 for the algae *Anabaena variabilis* to be 15.0-17.0 mg/L Se(IV). In a similar study, the 48h LC50 for *Oedogonium cardiacum* was found to be less than 0.1 mg/L (Nassos et al., 1980; as cited in Eisler, 1985b). Blue-green algae appear to be more resistant to Se(VI) than green algae as the lowest concentration to affect growth of the former lies at 10.0 mg/L Se(VI) (Vocke et al., 1980; as cited in EPA, 1987).

Bioaccumulation. Se accumulation is quite variable and not known to be affected by water hardness and temperature (Lemley, 1982; as cited in EPA, 1987). Nassos et al. (1980; as cited in Eisler, 1985b) found short-term exposure yielded BCFs of 460 for the mosquitofish and 32,000 for the freshwater gastropod. Long-term studies yielded lower BCFs; 6 for the common carp after an 85d exposure to 1.0 mg/L Se. Target organs for the carp were the kidney and liver (Sato et al., 1980; as cited in Eisler, 1985b). Se(VI) bioaccumulation factors for the fathead minnows ranged from 21 to 52 (Bertram and Brooks, 1986; as cited in EPA, 1987). Adams (1976; as cited in EPA, 1987) looked at the uptake of Se(IV) by fathead minnows. Initially, concentrations in the tissue and whole body increased rapidly, however, after 8d the rate fell off until steady state was approached, but never reached, at 96d.

Aquatic Mode of Action. Ellis et al. (1937; as cited in Eisler, 1985b) observed a number of symptoms typical of selenium toxicosisin fish: loss of equilibrium, lethargy, contraction of dermal chromatophores, loss of coordination, muscle spasms, protruding eyes, swollen abdomen, liver degeneration, reduction in blood hemoglobin and erythrocyte number, and increase in white blood cells.

Water Quality Criteria. The species of selenium are not differentiated in the water quality criteria. The acute and chronic NAWQ criteria for the protection of aquatic organisms are 0.02 and 0.005 mg/L, respectively (EPA, 1987).

Table 13. Toxicity of Se(IV) to aquatic organisms (EPA, 1987).

Conc. (mg/L)	Effect
203	Leech (*Nepheiopsis obscura*) LC50
42.5	Midge(*Tanytarsus dissimilis*) LC50
35	Common carp (*Cyprinus carpio*) LC50
34.91	Snail (*Aplexa hypnorum*) LC50
30.18	White sucker (*Cotostomus commersoni*) LC50
28.5	Bluegill (*Lepomis macrochirus*) LC50
26.1	Goldfish (*Carassius auratus*) LC50
25.93	Midge (*Chironomus plumosus*) LC50
24.1	Snail (*Physa sp.*) LC50
13.6	Channel catfish (*Ictalurus punctatus*) LC50
12.6	Mosquitofish (*Gambusia affinis*) LC50
11.7	Yellow perch (*Perca flavescens*) LC50
10.49	Rainbow trout (*Onchorhynchus mykiss*)LC50
10.2	Brook trout (*Salvelinus fontinalis*) LC50
6.5	Flagfish (*Jordonella floridae*) LC50
3.87	Water flea (*Daphnia pulex*) EC50
2.704	Amphipod (*Gammarus pseudolimnaeus*) LC50
1.783	Striped bass (*Morone saxatilis*) LC50
1.7	Hydra (*Hydra sp.*) LC50
1.601	Fathead minnow (*Pimephales promelas*) LC50
0.8558	Water flea (*Daphnia magna*) EC50
0.6928	Water flea (*Daphnia pulex*) CV
<0.6036	Water flea (*Ceriodaphnia affinis*) EC50
0.304	Amphipod (*Hyalella azteca*) LC50
0.1615	Water flea (*Daphnia magna*) CV

Conc. (mg/L)	Effect
0.1127	Fathead minnow (*Pimephales promelos*) CV
0.09165	Water flea (*Daphnia magna*) CV
0.0883	Rainbow trout (*Onchorhynchus mykiss*)CV

Table 14. Toxicity of selenium (VI) to aquatic organisms (EPA, 1987).

Conc. (mg/L)	Effect
442.0	Leech (*Nephelepsis obscura*) LC50
193.0	Snail (*Aplexa hypnorum*) LC50
66.0	Channel catfish (*Ictalurus punctatus*) LC50
63.0	Bluegill (*Lepomis macrochirus*) LC50
47.0	Rainbow trout (*Onchorhynchus mykiss)* LC50
20.0	Midge (*Paratanytarsus parthenogeneticus*) LC50
7.30	Hydra (*Hydra sp.*) LC50
5.50	Fathead minnow (*Pimephales promelas*) LC50
2.891*	Rainbow trout (*Onchorhynchus mykiss)* CV
1.999	Water flea (*Daphnia magna*) CV
1.450	Water flea (*Daphnia magna*) EC50
0.760	Amphipod (*Hyalella azteca*) LC50
0.5655	Fathead minnow (*Pimephales promelas*) CV
0.246	Water flea (*Daphnia pulicaria*) EC50
0.06538	Amphipod (*Gammarus pseudolimnaeus*) LC50

SILVER

Silver (Ag), a basic element, occurs naturally in the environment as a soft, silver colored metal (ATSDR, 1989b). It also occurs in a powdery white or dark gray to black compound. Silver is found at an average of 0.1 mg/kg in the earth's crust and about 0.3 mg/kg in soils. Silver metals and silver compounds are used in the production of surgical protheses, fungicides, coinage, jewelry, and dental fillings (Fisher et al., 1984). The accumulation of silver in marine algae appears to result from adsorption rather than uptake; bioconcentration fators of 13,000 - 66,000 have been reported (Fisher et al., 1984; ATSDR, 1989b).

Acute Toxicity. Toxicity of silver to freshwater fish and invertebrates is dependent upon water hardness and chloride content, with silver being more toxic in soft and low chloride water (EPA 1980-Ag). Toxicity of silver is dependent upon the form of the element. In tests with fathead minnow, free silver ion is the form of silver most acutely toxic to fish, with a 96-h LC50 of 0.016 mg/L, followed by silver thiosulfate complex (280-360 mg/L), and silver sulfide (>240 mg/L).

Acute toxicity data are available for four invertebrate species (EPA 1980-Ag), with acute values ranging from 0.00683 mg/L for *Daphnia magna* to 52.4 mg/L for the scud *Gammarus pseudolimnaeus*, both of which were tested in Lake Superior water. Acute values for fish in a hardness of 100 mg/L Ca range from 0.309 mg/L for the bluegill *(Lepomis macrochirus)* to 0.0106 mg/L for the speckled dace (*Rhinichthys osculus*) (EPA, 1980-Ag) (Table 15).

Chronic Toxicity. Chronic values for rainbow trout listed in EPA (1980-Ag) are between 0.00009 and 0.0159 mg/L. One of these studies was an 18-month study to evaluate the effects on silver nitrate in soft water on survival and growth of rainbow trout was conducted by Davies et al., (1978). The exposure was initiated with eyed embryos which hatched after 26 days. The "no-effect" concentration was between 0.00009 and 0.00017 mg/L, based on mortality data. However, this concentration does not reflect possible effects of silver on spawning behavior or reproduction. From 3.5 months of exposure to the end of the experiment, significant decreases in growth occurred in fish exposed to 0.00069 mg/L Ag. Egg and sac-fry mortality was 52% in the 0.00069 mg/L concentration.

Results of exposing fathead minnow embryos and larvae to silver sulfide at 11 mg/L (total silver) resulted in no significant effects on average wet weight or total length of larvae after 30 days of continuous exposure. Exposures of silver thiosulfate complex at total silver concentrations greater than 35 mg/L caused significant effects in survival and total length. Concentrations of 140 mg/L total silver resulted in a significant reduction in egg hatch (LeBlanc et al., 1984).

Table 15. Toxicity of silver to aquatic organisms (EPA 1980- Ag).

Concentration (mg/L)		Effect
100 mg hardness	200 mg hardness	
15.9	52.4	scud (*Gammarus pseudolimnaeus*) LC50
15.2	50.1	rotifer (*Philodina acuticornis*) LC50
11.3	37.3	midge (*Tanytarsus dissimilis*) LC50
0.309	1.020	bluegill (*Lepomis macrochirus*) LC50

Concentration (mg/L)		Effect
100 mg hardness	200 mg hardness	
0.046	0.113	rainbow trout (*Oncorhynchus mykiss*) LC50
0.0339	0.1118	flagfish (*Jordanella floridae*) LC50
0.0271	0.0765	fathead minnow (*Pimephales promelas*) LC50
0.011	0.036	mottled sculpin (*Cottus bairdi*) LC50
0.0106	0.0350	speckled dace (*Rhinichthys osculus*) LC50
0.00791	0.00791	water flea (*Daphnia magna*) CV
0.00683	0.03484	water flea (*Daphnia magna*) EC50
0.0041	0.0134	NAWQC acute value
0.0012	0.0012	rainbow trout (*Oncorhynchus mykiss*) CV

[a] Acute effect levels were converted based on a 100 mg/L water hardness. Slopes used for the conversion were associated with individual species, where specified in the Criteria document. Otherwise, 1.72 was used. Chronic values were not converted based on water hardness, since no correlation was evident. A chronic NAWQC has not been determined.
[b] Acute effect levels were converted based on a 200 mg/L water hardness.

THALLIUM

Thallium (Tl) is a widely distributed metal, occurring at concentrations of approximately 1 mg/kg in the earth's crust (Kazantzis, 1979). Tl exists as Tl(II) or the more stable, and soluble, Tl(I) and is soluble over a wide range of pH (Kwan and Smith, 1991). Industrial uses of thallium include alloys, electronic devices, special glass and explosives (Zitko, 1975). Coal-fired power plants are major sources of Tl air pollution due to its presence in flyash (Wallwork-Barber et al., 1985). The international market for thallium is limited, therefore its removal from mining effluent is of low priority (Zitko et al., 1975). Thallium has been used since the 1920s as a rodenticide and is a major primary and secondary source of poisoning for raptors and other predatory mammals (Crabtree, 1962; Robinson, 1948: as cited in Bean and Hudson, 1976). Due to their high toxicity to larger mammals, their use against larger predatory animals was cancelled in 1972 (Zitko, 1975).

Chronic Toxicity. LeBlanc and Dean (1984) exposed fathead minnows (48h post fertilization) to Tl as thallium sulfate for 30d. At 0.72 mg/L none of the larvae hatched and at 0.35 mg/L none survived after 30d. 0.04 mg/L significantly reduced larval survivability and was considered the CV.

Bioaccumulation. Uptake of Tl by aquatic plants appears to be a metabolically mediated process due to its strong dependence on temperature and light conditions. Optimal conditions for uptake occur at pH 6 and temperatures above 12°C. Mechanisms of absorption in *Lemna minor* L. became saturated at concentrations above 204.4 mg/L after which, absorption ceased to occur, despite increased concentrations of Tl (Kwan and Smith, 1991).

Aquatic Mode of Action. Due to its low complexation ability the toxic action of Tl, unlike most metals, is not affected by the presence of humic acid or water hardness (O'Shea, 1972: as cited in Zitko et al., 1975; Zitko 1975). Hypertension in fish may be a reaction to the oxidation of Tl(I) to (III) inhibiting ATPase of amino storing granules, causing abnormalities in catecholamine metabolism (Burger and Starke, 1969: as cited in Zitko, 1975).

Water Quality Criteria. Suter and Tsao (1996) calculated SAV and SCV values for Tl(I) of 105.2 mg/L and 12 mg/L, respectively.

URANIUM

Uranium (U) is a silvery white metal consisting of three semistable radioactive isotopes; U238, U235, and U234 (Brobst and Pratt, 1973) making up approximately 3-4 mg/kg of the earth's crust (Merritt, 1971). Despite their radioactive properties, metallic uranium and particles of insoluble uranium compounds are biologically inert, its chemical toxicity being exerted only by its aqueous ions (Durbin and Wrenn, 1975). Aqueous ions have been identified for uranium (III), uranium (IV), uranium (V), and uranium (VI), but only uranium (IV) and uranium (VI) are stable in solution. In a solution of low acidity, uranium (IV) hydrolyzes to form insoluble hydroxides (Durbin and Wrenn, 1975). Uranyl nitrate and uranyl fluoride are 1.4–2 times more toxic than UCl_5, UCl_4, UO_3, or $NO_2U_2O_7$ and 3 times more toxic than $(NH_4)_2U_2O_7$ (Durbin and Wrenn, 1975). Uranium-235 is the most radioactive of the uranium isotopes. Other uranium isotopes including uranium-233, -234, and -238 have low specific activities, long half-lives, and have lower potential to cause radiation induced diseases (ATSDR, 1990).

In its radioactive elemental form, U fuels nuclear reactions, and is used in the manufacture of nuclear weapons and amunition. In its natural or depleted form U is used as counterweights in airplanes and as shielding material (Burkart, 1991)

Acute Toxicity. Relatively little aquatic toxicity data is available for uranium. The only standard data are LC50s for fathead minnow with values for various uranium salts ranging from 2.8 to 135 mg/L (Cushman et al., 1977). Toxic concentrations from nonstandard and poorly documented tests fall within this range.

ZINC

Zinc (Zn) is an essential trace element in all organisms; it assures the stability of biological molecules and structures such as DNA, membranes, and ribosomes (Eisler, 1993). It is used commercially primarily in galvanized metals and metal alloys, but zinc compounds also have wide applications as chemical intermediates, catalysts, pigments, vulcanization activators and accelerators in the rubber industry, UV stabilizers, and supplements in animal feeds and fertilizers. Zinc compounds are also used in rayon manufacture, smoke bombs, soldering fluxes, mordants for printing and dyeing, wood preservatives, mildew inhibitors, deodorants, antiseptics, and astringents (Lloyd, 1984; ATSDR, 1989a). Zinc phosphide is used as a rodenticide. Zinc makes up about 0.002% of the earth's crust (NAS, 1980) and occurs in many forms in natural waters and aquatic sediments.

In freshwater with pH >4 and <7, the dominant forms of dissolved zinc are the free ion (aquo ion complex) (98%) and zinc sulfate (2%) (Campbell and Stokes, 1985), whereas at pH 9.0, the dominant forms are the monohydroxide ion (78%), zinc carbonate (16%), and the free ion (6%) (EPA, 1987-Zn).

Zinc occurs in nature as a sulfide, oxide, or carbonate (Eisler, 1993). It is divalent in solution. Zinc interacts with many chemicals, and it may diminish the toxic effects of cadmium and protect against lead toxicosis in terrestrial animals (Eisler, 1993). Background concentrations seldom exceed 0.040 mg/L in water or 200 mg/kg in soil or sediment (Eisler, 1993).

Although it is essential for normal growth and reproduction (Prasad, 1979; Stahl et al., 1989) and important to central nervous system function (Eisler, 1993), the primary toxic effect of zinc is on zinc-dependent enzymes that regulate RNA and DNA. It is most harmful to aquatic life in conditions of low pH, low alkalinity, low dissolved oxygen, and elevated temperature. Zinc is relatively nontoxic in mammals, but excessive intake can cause a variety of effects. It is not known to be carcinogenic by normal exposure routes (Eisler, 1993).

Toxicity to Aquatic Plants. Although freshwater plants are often more sensitive to zinc than freshwater animals, the range of toxicity values was much greater: growth of the algae *Selenastrum capricornutum* was inhibited by 0.030 mg/L whereas several other species of green algae had 96-hour EC50s that exceeded 200.0 mg/L (EPA, 1987-Zn).

INORGANICS

BENZENE

Toxicity to Aquatic Organisms. Suter and Tsao (1996) reported lowest chronic values for aquatic plants and daphnids of 525.0 and >98.0 mg/L, respectively. Tier II values include a SAV of 2.3 mg/L and a SCV of 0.13 mg/L. Out of the three invertebrate studies cited, LC50s range from 100.0 mg/L for *Chironomus thummi* to 620.0 mg/L for *D. Magna*. Out of the seven vertebrate studies cited, LC50s range from 4.63 mg/L for *Oncorhynchus gorbuscha* to 425.0 mg/L for *Ictalurus punctatus*.

BIS (2-ETHYLHEXL) PHTHALATE

Bis(2-ethylhexyl)phthalate (BEHP) or di(2-ethylhexyl)phthalate is a colorless oily liquid that is extensively used as a plasticizer in a wide variety of industrial, domestic and medical products. The wide-spread uses of bis(2-ethylhexyl)phthalate have made the compound, along with other phthalic acid esters, ubiquitous in the environment. It has been detected in ground water, surface water, drinking water, air, soil, plants, fish and animals (Sittig, 1985; Sandmeyer and Kirwin, 1978). While bioaccumulation factors for bis(2-ethylhexyl)phthalate at lower trophic levels are high, because it is rapidly metabolized, levels in higher trophic levels are generally lower than those observed at lower trophic levels (Peakall, 1975).

Toxicity to Aquatic Organisms. Suter and Tsao (1996) reported a lowest chronic value for daphnids of 0.912 mg/L. Tier II values include a SAV of 0.0266 mg/L and a SCV of 0.003 mg/L. Out of the four invertebrate studies cited, LC50s range from >32.0 for the amphipod *(Gammarus pseudolimnaeus)* to 0.133 mg/L for *D. pulex*. Out of the seven vertebrate studies cited, LC50s range from >0.16 mg/L for the fathead minnow *(Pimephales promelas)* to >770.0 mg/L for the bluegill *(Lepomis macrochirus)*.

CARBON DISULFIDE

Toxicity to Aquatic Organisms. Suter and Tsao (1996) reported lowest chronic values for fish and daphnids of 9.538 and 0.244 mg/L, respectively. Tier II values include a SAV of 0.01653 mg/L and a SCV of 0.00092 mg/L. The only study available for carbon disulfide yielded a LC50 of 4.0 for the guppy *(Poecilia reticulata)* in circumneutral water.

CARBON TETRACHLORIDE

Toxicity to Aquatic Organisms. Suter and Tsao (1996) reported lowest chronic values for fish and daphnids of 1.97 and 5.58 mg/L, respectively. Tier II values include a SAV of 0.1757 mg/L and a SCV of 0.0098 mg/L. Fathead minnows *(Pimephales promelas)* are the only known test organisms yielding an LC50 between 41.4 and 43.3 mg/L.

ETHYLBENZENE

Toxicity to Aquatic Organisms. Suter and Tsao (1996) reported lowest chronic values for fish, daphnids, and aquatic plants of >0.44, 12.922, and >438.0 mg/L, respectively. Tier II values include a SAV of 0.13 mg/L and a SCV of 0.0073 mg/L. Known values include an EC50 of 8.45 mg/L for the fathead minnow and a LC50 of 9.6 mg/L for the guppy *(Poecilia reticulata)*.

NAPTHALENE

Naphthalene is a white solid substance used in the manufacture of dyes, resins and in mothballs. It is released to the air from the burning of coal and oil and from the use of mothballs containing naphthalene. Naphthalene may also be released into the air by coal tar production and wood preservation. In water and soil, naphthalene is either destroyed by bacteria or evaporated into the air within a few hours or days (ATSDR, 1989c). Naphthalene breaks down readily in the environment and is easily metabolized by various organisms (ATSDR, 1989c).

Toxicity to Aquatic Organisms. Suter and Tsao (1996) reported lowest chronic values for fish, daphnids, and aquatic plants of 0.62, 1.163, and 33.0 mg/L, respectively. Tier II values include a SAV of 0.186 mg/L and a SCV of 0.012 mg/L. Two daphnid invertebrate studies found EC50s of 2.194 and 4.663 mg/L for *D. magna* and *D. pulex*, respectively. Vertebrate LC50 values range from 1.6 mg/L for the rainbow trout *(Oncorhynchus mykiss)* to 7.9 mg/L for the fathead minnow. A chronic value of 0.619 mg/L was found for the fathead minnow.

POLYCHLORINATED BIPHENYLS

Polychlorinated biphenyls (PCB's) are a family of man-made chemicals consisting of 209 individual compounds with varying toxicity (ATSDR, 1989d). Aroclor is the trade name for PCB's made by Monsanto. Because of their insulating and nonflammable properties, PCB's were widely used in industrial applications such as coolants and lubricants in transformers, capacitors, and electrical equipment (ATSDR, 1989d). The United States stopped manufacturing PCB's in 1977 due to evidence that they accumulated in the environment. Although PCB's are no longer manufactured or used in the United States, they remain present and will continue to become a widespread environmental contaminant. The biodegradation of PCB's in soil is slow, especially in soils with high organic carbon content (ATSDR, 1993).

Table 1. Toxicity of PCBs to aquatic life (EPA, 1980).

Conc. (mg/L)	Effect
0.283	damselfly (*Ischnura verticalis*) LC50
0.046	Scud (*Gammarus pseudolimnaeus*) LC50
0.033	fathead minnow (*Pimephales promelas*) LC50
0.019	redear sunfish (*Lepomis microlophus*) LC50
0.010	Scud (*Gammarus fasciatus*) LC50
0.00514	cladoceran (*Daphnia magna*) CV
0.00402	Scud (*Gammarus pseudolimnaeus*) CV
0.0023	largemouth bass (*Micropterus salmoides*) LC50
0.0020	rainbow trout (*Oncorhynchus mykiss*) LC50
0.00186	fathead minnow (*Pimephales promelas*) CV
0.0010	brook trout (*Salvelinus fontinalis*) CV
0.00080	Midge (*Tanytarsus dissimilis*) CV

TOLUENE

Toxicity to Aquatic Organisms. Suter and Tsao (1996) reported lowest chronic values for fish, daphnids, and aquatic plants of 1.269, 25.229, and 245.0 mg/L, respectively. Tier II values include a SAV of 0.12 mg/L and a SCV of 0.0098 mg/L. Fathead minnows were the only test species found with LC50 values ranging from 18.0 to 36.2 mg/L.

XYLENE

Toxicity to Aquatic Organisms. Suter and Tsao (1996) reported a lowest chronic value for fish to be 62.308 mg/L. Tier II values include a SAV of 0.2323 mg/L and a SCV of 0.013 mg/L. Bluegills *(Lepomis macrochirus)* yielded a LC50 of 15.7 mg/L, while fathead minnows had EC50 values of 15.3 and 14.8 mg/L.

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TOXICITY TO BENTHIC INVERTEBRATES

ORGANICS

ANTIMONY

Antimony (Sb) is a naturally occurring metalloid element (displaying both metallic and nonmetallic properties) existing in valence states of 3 and 5 (Budavari, 1989; ATSDR, 1990a). Metallic antimony and a few trivalent antimony compounds are the most significant regarding exposure potential and toxicity (ATSDR, 1990). Antimony is used in metallurgical processes, paints and enamels, various textiles, rubber, and fire retardation (antimony trioxide). Some antimonials such as potassium antimony tartrate have been used medicinally as parasiticides (Beliles, 1979).

Toxicity in Sediment to Benthic Invertebrates. Freshwater data for the toxicity of antimony in sediment is not available, however, Long and Morgan (1991) reported data for the toxicity of antimony in sediment for marine water. The data from Commencement Bay, Washington indicated that toxicity to both *Rhepoxynius abronius* and the larvae of the oyster *Crassostrea gigas* increased with increasing antimony concentrations in the sediment. Data collected from San Francisco Bay, however, showed no relation between toxicity to amphipods and antimony concentration. Sediments that were least toxic or not toxic had higher antimony concentrations than sediments that were most toxic or significantly toxic. The suggested Effects Range-Low (ER-L) and Effects Range-Medium (ER-M) values are 2.0 and 25 mg/kg, respectively.

ARSENIC

Arsenic (As) is a naturally-occuring metaloid found in air and all living organisms. It is present in the earth's crust at approximately 2 mg/kg and is sparingly soluble in water and body fluids. It occurs as two forms in ambient media, arsenic (III), usually the most toxic, and arsenic (V) (EPA, 1985-As) with its magnitude of bioavailability and toxicity dependent upon the oxidation state and temperature (McGeachy and Dixon, 1992). The state is dependent on environmental conditions, including Eh, pH, organic content, suspended solids and sediment. The relative toxicities of the various forms of arsenic apparently vary from species to species. Arsenic may be released into aquatic ecosystems by anthropogenic sources including the manufacture and use of arsenical defoliants and pesticides, electric generating stations, manufacturing companies, mineral or strip mines, steel production, fossil fuel combustion and smelting operations (Sorensen, 1991; McGeachy and Dixon, 1989; Ferguson and Gavis, 1972; NRCC, 1978) and natural leaching of the soils. Arsenic levels in a river ecosystem were found to be dependent upon the availability of arsenic, rain water dilution, extent of complexation with dissolved organic matter and possibly the metabolic activity of aquatic plants (Koranda et al. 1981). As soil clay concentration increases, arsenic adsorption into the soil increases as a function of soil pH, texture, iron, aluminum, organic matter and time (Woolson, 1977). Arsenic is known as one of the most toxic elements to fish with acute exposures resulting in immediate death (Sorensen, 1991).

Toxicity in Sediment to Benthic Invertebrates. Sediments of Waukegan Harbor, Wisconsin, which had more than 47 mg/kg arsenic caused 34% mortality in the amphipod *Hyalella azteca*. Sediment from the Sheboygan River, Wisconsin, which had 2.7 mg/kg arsenic caused significant mortality to the freshwater prawn, *Macrobrachium rosenbergii*. However, this sediment also was contaminated with metals and polychlorinated biphenyls (PCBs). At 2 rivers in Illinois, a low number of benthic macroinvertebrate taxa was associated with arsenic concentrations of 7.4 and 3.7 mg/kg. However, a high number of taxa were associated with 5.9 and 5.0 mg/kg arsenic in the same two rivers (studies cited in Long and Morgan, 1991).

Long et al., (1995) reported ER-L and ER-M values of 8.2 and 70 mg/kg, respectively. Only 11% of these documented studies indicated biological effects at concentrations between the ER-L and ER-M, while 63% of the studies at concentrations above the ER-M indicated biological effects (Table 1).

Table 1. Arsenic toxicity to benthic invertebrates in saline water (MacDonald et al., 1994)

Conc. (mg/kg)	Endpoint	Species
1.88	14d LC100	sandworm *(Nereis virens)*
4.33	1h EC98 (fertilization)	sea urchin *(Arbacia punctulata)*
4.65	48h LC25	sea urchin *(Arbacia punctulata)*
8.25	Chronic Marine EqP Threshold	aquatic biota
10.10	LC33	mysid shrimp *(Mysidopsis bahia)*
10.20	10d LC16	amphipod *(Ampelisca abdita)*
12.00	10d LC55	amphipod *(Hyallela azteca)*
12.80	96h LC>50	shrimp *(Paleamonetes pugio)*
16.00	EPA Acute Marine EP Threshold	aquatic biota
20.00	10d LC20	amphipod *(Rhepoxynius abronius)*
22.10	48h EC59 (abnormality)	bivalve
22.40	15m EC50	microtox *(Photobacterium phosphoreum)*
43.00	20d LC37	polychaete *(Neanthes arenaceodentata)*
50.70	48h EC92 (abnormality)	bivalve
58.70	48h EC23 (abnormality)	oyster
91.80	48h LC50	mummichog *(Fundulus heteroclitus)*
91.80	48h LC50	spot *(Leiostomus xanthurus)*
690.00	48h EC45 (abnormality)	oyster
2257.00	10d LC79	amphipod *(Rhepoxynius abronius)*

CADMIUM

Cadmium (Cd) occurs predominately in the form of free divalent cations in most well oxygenated, low organic matter, fresh waters (EPA 1985-Cd). However, both particulate matter and dissolved organic matter can bind cadmium in biologically unavailable forms. There is no evidence that cadmium is a biologically essential or beneficial element (Eisler, 1985). Cd toxicity is related to water hardness, with a reduction in toxicity associated with increased water hardness (EPA, 1985-Cd).

Toxicity in Sediment to Benthic Invertebrates. An Illinois harbor sediment containing 2.5 mg/kg cadmium resulted in 34% mortality of *Hyalella azteca*. A concentration of 1.98 mg/kg caused 95% mortality to *Hyalella azteca* in a Washington lake sediment. Significant mortality to the prawn *Macrobrachium rosenbergii* resulted from 2.8 mg/kg cadmium in a Wisconsin river (studies cited in Long and Morgan, 1991).

Confidence in the Long and Morgan (1991) ER-L and ER-M is very high, because data are available from many approaches, from multiple methods for some approaches, and are relatively consistent (Long and Morgan, 1991). The updated ER-L and ER-M (Long et al., 1995), which do not include freshwater data, also show good consistency. That is, 37% of the documented studies indicated biological effects at concentrations between the ER-L and ER-M, and 66% of the studies at concentrations above the ER-M indicated biological effects. However, resistance to cadmium is higher among marine species than among freshwater species (Eisler, 1985).

CHROMIUM

Chromium (Cr) occurs in the environment as either chromium (III) or chromium (VI). Trivalent chromium is an essential metal in animals, playing an important role in insulin metabolism (Larngard and Norseth, 1979). Hexavalent chromium is more toxic than chromium (III) because of its high oxidation potential and the ease with which it penetrates biological membranes (Steven et al., 1976; Taylor and Parr, 1978). Chromium (III), the predominant form in the environment, exhibits decreasing solubility with increasing pH, and is completely precipitated at a pH above 5.5. In most soils, chromium is primarily present as precipitated chromium (III), which is not bioavailable and has not been know to biomagnify through food chains in its inorganic form (Eisler, 1986). Chromium is released into the environment in the processing of chromate, electroplating, production at tanning and textile plants, pigment production, and cooling tower preservation. Cr is naturally released into the environment through the weathering of soils (Fishbein, 1976).

Toxicity in Sediment to Benthic Invertebrates. There is relatively little consistency in the effects data presented by NOAA (Long and Morgan, 1991). This may be due to the lack of chromium speciation data in the NOAA studies. All of the data were reported as total chromium, whereas the hexavalent form has been reported to be the most toxic. In Lake Union, Washington, a concentration of 20 mg/kg resulted in 95% mortality of *Hyalella azteca*. However, in the Dupage and Kishwaukee rivers in Illinois chromium levels of 34 and 29 mg/kg, respectively, had the highest number of benthic macroinvertebrate taxa, while concentrations of 60 and 43 mg/kg, respectively, has the lowest number of benthic macroinvertebrate taxa. In the Keweenaw Waterway of Michigan, 36 mg/kg of chromium was not toxic to *Daphnia magna,* but levels of 109 mg/kg were significantly toxic. In Torch Lake, Michigan, concentrations of 180 mg/kg of chromium resulted in significant mortality to *Daphnia magna* and *Hexagenia sp.* (studies cited in Long and Morgan, 1991). Long et al., (1995) reported ER-L and ER-M values of 81 and 370 mg/kg for chromium. The incidence of adverse effects was 95% in the probable-effects range for chromium, however, the incidence of effects in the probable-effects range was greatly influenced and exaggerated by data from multiple tests conducted in only two field surveys (Table 2).

Table 2. Chromium toxicity to benthic invertebrates in saline water (MacDonald et al., 1994).

Conc. (mg/kg)	Endpoint	Species
6.25	Chronic Marine EqP Threshold	aquatic biota
17.40	48h LC25	*Arbacia punctulata* (sea urchin)
31.30	10d LC83	*Leptocheirus plumulosus* (amphipod)
35.70	20d LC95	*Leptocheirus plumulosus* (amphipod)
48.30	10d LC55	*Hyalella azteca* (amphipod)
54.00	10d LC55	*Hyalella azteca* (amphipod)
57.90	1h EC98 (fertilization)	*Arbacia punctulata* (sea urchin)
59.90	48h EC85 (devlopment)	*Arbacia punctulata* (sea urchin)
60.00	48h Significant increase in burrowing time	*Macoma balthica* (bivalve)

Conc. (mg/kg)	Endpoint	Species
60.40	low density	echinodermata
61.20	low density	arthropods
62.00	low spec. richness	benthic
77.40	EC50	*Photobacterium phosphoreum* (Microtox)
87.30	Sediments Devoid of Feral Clams	*Macoma balthica* (bivalve)
90.00	24h - avoidance	*Macoma balthica* (bivalve)
93.70	10d LC32	*Ampelisca abdita* (amphipod)
108.00	20d EC<90 (emergence)	*Hyalella azteca* (amphipod)
108.00	10d LC29	*Lepidactylus dytiscus* (amphipod)
108.00	10d EC90 (reburial)	*Lepidactylus dytiscus* (amphipod)
108.00	20d EC<90 (emergence)	*Lepidactylus dytiscus* (amphipod)
110.00	48h EC77 (abnormality)	*Crassostrea gigas* (oyster)
146.00	low abundance	arthropods
157.00	low spec. richness	benthic
160.00	14d reduced growth rate	*Chromadorina germanice* (nematode)
197.00	low abundance	benthic
201.00	low abundance	echinoderm
211.00	low abundance	echinoderms
227.00	low abundance	phoxocephalids
227.00	low abundance	amphipods
260.00	Chemical Criteria	benthic
369.00	14d LC100	*Nereis virens* (sandworm)
383.00	low density	echinoderm
416.00	low spec. richness	benthic
523.00	low density	echinoderm
523.00	low density	*Foraminifera* (sponge)
523.00	low density	*Ophiuroidea* (brittle star)
527.00	low density	amphipod
527.00	low density	phoxocephalid
669.00	10d LC21	*Rhepoxynius abronius* (amphipod)
669.00	low density	mollusca
682.00	low density	crustacea
682.00	low density	phoxocephalid
682.00	low density	amphipod
682.00	low spec. richness	macro benthos
1646.00	48h LC50	*Leiostomus xanthurus* (spot)
1646.00	48h LC50	*Fundulus heteroclitus*(mummichog)

COPPER

Copper (Cu) occurs in natural waters primarily as the divalent cupric ion in free and complexed forms (EPA 1985-Cu). Copper is a minor nutrient for both plants and animals at low concentrations, but is toxic to aquatic life at concentrations only slightly higher. Concentrations of 0.001 to 0.010 mg/L are usually reported for unpolluted surface waters in the United States.

Common copper salts, such as the sulfate, carbonate, cyanide, oxide, and sulfide are used as fungicides, as components of ceramics and pyrotechnics, for electroplating, and for numerous other industrial applications (ACGIH, 1986). The largest anthropogenic releases of copper to the environment result from mining operations, agriculture, solid waste, and sludge from sewage treatment plants.

Toxicity in Sediment to Benthic Invertebrates. A concentration of 156 mg/kg Cu caused 95% mortality to *Hyalella azteca* at Lake Union, Washington. In Waukegan Harbor, Illinois, there was 34% mortality to the same species at a concentration of 19.5 mg/kg. In Illinois, a high number of benthic invertebrate taxa were found in one river with a sediment copper concentration of 62 mg/kg; although another Illinois river had a high number of taxa at 19.5 mg/kg and a low number of taxa at a concentration of 45 mg/kg (studies cited in Long and Morgan, 1991). Long et al., (1995) reported ER-L and ER-M values of 34 and 270 mg/kg for copper. Confidence in these values is high because 84% of the studies at concentrations above the ER-M indicated biological effects (Table 3).

Table 3. Copper toxicity to benthic invertebrates in sediments of saline waters (MacDonald et al., 1994).

Conc. (mg/kg)	Endpoint	Species
1.00	EC98 (moderate diversity)	benthic
3.78	48 h LC25	*Arbacia punctulata* (sea urchin)
8.08	10 d LC55	*Hyalella azteca* (ampipod)
10.70	low abundance	oligochaeta
11.30	low density	annelida
12.60	10 d LC46	*Lepidactylus dytiscus* (amphipod)
12.70	48 h EC85 (development)	*Arbacia punctulata* (sea urchin)
13.60	ET50 (burrowing time)	*Protothaca staminea* (littleneck clam)
14.00	low density	echinodermata
14.20	10 d EC90 (reburial)	*Lepidactylus dytiscus* (amphipod)
14.20	low density	arthropoda
14.20	20 d EC<90 (emergence)	*Lepidactylus dytiscus* (amphipod)
14.20	20 d EC<90 (emergence)	*Hyalella azteca* (ampipod)
14.20	10 d LC29	*Lepidactylus dytiscus* (amphipod)
14.50	low richness	benthic
16.80	20 d EC<90 (emergence)	*Hyalella azteca* (ampipod)
16.80	20 d EC<80 (emergence)	*Lepidactylus dytiscus* (amphipod)
16.80	10 d EC83 (reburial)	*Lepidactylus dytiscus* (amphipod)
16.80	10d growth	*Lepidactylus dytiscus* (amphipod)
23.40	ET50 - 69h (reburial)	*Protothaca staminea* (littleneck clam)
23.40	ET50 - 63h (reburial)	*Protothaca staminea* (littleneck clam)
30.00	10 d LC16	*Ampelisca abdita* (amphipod)
32.40	ET50 - 25h (burial)	*Protothaca staminea* (littleneck clam)
32.40	ET50 - 97h (reburial)	*Protothaca staminea* (littleneck clam)
32.40	ET50 - 300h (reburial)	*Protothaca staminea* (littleneck clam)
32.40	ET50 - 101h (burial)	*Protothaca staminea* (littleneck clam)
34.00	EPA Chronic Marine EP Threshold	aquatic biota

Conc. (mg/kg)	Endpoint	Species
34.00	Chronic Marine EqP Threshold	aquatic biota
38.20	48 d LC25	*Protothaca staminea* (littleneck clam)
38.20	48 d LC15	*Protothaca staminea* (littleneck clam)
43.00	20 d LC52	*Neanthes sp.* (polychaete)
43.80	1 h EC98 (fertilization)	*Arbacia punctulata* (sea urchin)
54.00	EPA Acute Marine EP Threshold	aquatic biota
67.00	48 h Significant increase in burrowing time	*Macoma balthica* (bivalve)
68.20	48 h EC56 (abnormal)	bivalve
71.00	low abundance	arthropods
72.00	EC50	*Photobacterium phosphoreum* (Microtox)
73.20	low richness	benthic
76.00	48 h EC59 (abnormal)	bivalve
84.60	10 d LC67	*Rhepoxynius abronius* (amphipod)
87.80	48 h EC92 (abnormal)	bivalve
96.70	low abundance	echinoderm
98.70	48 h LC92	mussel
103.00	10 d LC32	*Ampelisca abdita* (amphipod)
106.00	48 h EC23 (abnormal)	oyster
109.00	low abundance	echinoderms
114.00	48 h EC67 (abnormal)	mussel
117.00	10 d LC31	*Ampelisca abdita* (amphipod)
118.00	10 d LC26	*Rhepoxynius abronius* (amphipod)
121.00	low abundance	phoxocephalids
121.00	low abundance	amphipods
124.00	10 d LC83	*Leptocheirus plumulosus* (amphipod)
125.00	10 d EC31 (emergence)	*Rhepoxynius abronius* (amphipod)
125.00	EC23 (emergence)	*Corophium volutator* (amphipod)
130.00	10 d EC37 (avoidance)	amphipod
130.00	10 d LC95	amphipod
135.00	Sediments devoid of feral clams	*Macoma balthica* (bivalve)
147.00	96 h LC>50	*Palaemonetes pugio* (shrimp)
150.00	24h - avoidance	*Macoma balthica* (bivalve)
157.00	20 d LC95	*Leptocheirus plumulosus* (amphipod)
164.00	EC50	*Photobacterium phosphoreum* (Microtox)
181.00	10 d LC52	*Grandidierella japonica* (amphipod)
187.00	low density	echinoderm
192.00	10 d LC62	*Rhepoxynius abronius* (amphipod)
196.00	48 h LC52	*Mulinia lateralis* (bivalve)
202.00	0.25 h EC50 (extract)	*Photobacterium phosphoreum* (Microtox)
220.00	20 d EC60 (abnormal development)	*Dendraster excentricus* (echinoderm)
258.00	low richness	benthic
259.00	10 d LC81	*Rhepoxynius abronius* (amphipod)

Conc. (mg/kg)	Endpoint	Species
270.00	low density	phoxocephalid
270.00	low density	amphipod
337.00	20 d LC37	*Neanthes arenaceodentata* (polychaete)
361.00	10 d LC55	*Hyalella azteca* (ampipod)
412.00	low density	polychaeta
455.00	low density	*Foraminifera foraminifera* (sponge)
455.00	low density	*Ophiuroidea ophiuroidea* (brittle star)
455.00	low density	echinoderm
581.00	low density	phoxocephalid
581.00	low richness	macro benthos
581.00	low density	crustacea
581.00	low density	amphipod
592.00	10 d LC21	*Rhepoxynius abronius* (amphipod)
592.00	low density	mollusca
612.00	14 d LC100	*Nereis virens* (sandworm)
918.00	48 h EC45 (abnormal)	oyster
1071.00	48 h LC50	*Fundulus heteroclitus* (mummichog)
1071.00	48 h LC50	*Leiostomus xanthurus* (spot)
2820.00	10 d LC79	*Rhepoxynius abronius* (amphipod)

IRON

Because iron (Fe) is the fourth most abundant element in the earth's crust, it commonly occurs at high concentrations in whole water analyses. Dissolved concentrations in water and soil are dependent upon redox conditions and pH. Fe typically occurs in water between 0.01 and 1.4 mg/L (Jorgensen et al., 1991; as cited in Gerhardt, 1994) with occurrence increasing in the presence of humic acids (Gerhardt, 1993). At lower concentrations, iron is an essential trace metal in both the plant and animal kingdoms because of its role in oxygen and energy transport. Iron occurs in the +1,+2 and +3 valence states and speciation from the +2 to the +3 state has been known to occur between pH 4.5 and 7. However, increased toxicity of iron at in acidic conditions may be a result of the photoreduction from +3 to the +2 state, or the destabilization of weaker iron complexes (Gerhardt, 1994). The most common dissolved inorganic form of iron is $Fe(OH)_2^+$ (Dave 1984). Toxicity of iron to aquatic organisms has received little attention because it is observed in unusual circumstances such as acid mine drainage or discharge of acidic metal working wastes.

Toxicity in Sediment to Benthic Invertebrates. The Ontario Ministry of the Environment (MOE) has prepared provincial sediment quality guidelines (SQGs). These values are based on Ontario sediments and benthic species from a wide range of geographical areas within the province. The lowest effect level (low) is the level at which actual ecotoxic effects become apparent. The severe effects level (severe) represents contaminant levels that could potentially eliminate most of the benthic organisms. These "low" and "severe" effects levels are 3% (30,000 mg/kg) and 4% (40,000 mg/kg), respectively (Jones et al., 1996).

LEAD

Lead (Pb), a comparatively rare metal, averages 16 mg/kg in the earth's crust, and is neither essential nor beneficial in living organisms (Eisler, 1988). Lead has adverse effects on survival, growth, reproduction, development, behavior, learning, and metabolism. In general, organic lead compounds are more toxic than inorganic compounds, biomagnification of lead is minimal, and younger organisms are more susceptible to lead toxicity (Eisler, 1988). Although lead occurs in a variety of forms in the aquatic environment, the relative toxicities of these forms are not well defined (EPA, 1985-Pb).

Toxicity in Sediment to Benthic Invertebrates. Although a relatively large amount of data exists for lead and measures of effects in sediments, there are no spiked sediment bioassays and a wide concentration range exists with the associated effects (Long and Morgan, 1991). Freshwater biota may be more sensitive to lead than marine species (Eisler, 1988).

Significant effects were observed in *Daphnia magha* exposed to Keweenaw Waterway sediments containing 27 mg/kg lead. Taxa richness of macroinvertebrate communities in the Kishwaukee River were reduced in sediments containing 31 mg/kg and taxa-rich in sediment containing 21 mg/kg. Significant toxicity to *D. magna* and *Hexagenia limbata* was observed at 110 mg/kg in sediments of Torch Lake, Michigan (studies cited in Long and Morgan, 1991). Long et al., (1995) reported ER-L and ER-M values of 46.7 and 218 mg/kg for lead. Confidence is high for these values because 90% of the studies at concentrations above the ER-M indicated biological effects (Table 4).

Table 4. Toxicity of lead to benthic invertebrates in sediment of saline water (MacDonald et al., 1994).

Conc. (mg/kg)	Endpoint	Species
10.00	1h EC55 (fertilization)	*Arbacia punctulata* (sea urchin)
12.30	moderate abundance	oligocheate worm
18.20	low abundance	oligocheate worm
20.80	low abundance	copepoda
23.00	10d EC90 (reburial)	*Lepidactylus dytiscus* (amphipod)
23.00	20d EC<90 (emergence)	*Hyalella azteca* (amphipod)
23.00	10d LC29	*Lepidactylus dytiscus* (amphipod)
23.00	20d EC<90 (emergence)	*Lepidactylus dytiscus* (amphipod)
24.20	10d LC46	*Lepidactylus dytiscus* (amphipod)
28.00	10d LC20	*Rhepoxynius abronius* (amphipod)
32.00	48h Significant Increase in burrowing time	*Macoma bathica* (bivalve)
33.00	Chronic Marine EqP	aquatic biota
33.00	EPA Chronic Marine EP	aquatic biota
37.80	20d EC<80 (emergence)	*Lepidactylus dytiscus* (amphipod)
37.80	20d EC<90 (emergence)	*Hyalella azteca* (amphipod)
37.80	10d EC83 (reburial)	*Lepidactylus dytiscus* (amphipod)
41.30	96h LC>50	Palaemonetes pugio
41.30	low density	annelida
41.60	low density	echinodermata
42.10	10d LC34	*Rhepoxynius abronius* (amphipod)

Conc. (mg/kg)	Endpoint	Species
42.40	low density	arthropods
43.10	low richness	benthic
48.00	low abundance	arthropods
51.00	low richness	benthic
58.90	48h EC56 (abnormal)	bivalve
63.40	48h EC59 (abnormal)	bivalve
64.00	low abundance	echinoderm
68.70	low abundance	echinoderm
73.60	1h EC98 (fertilization)	*Arbacia punctulata* (sea urchin)
74.00	24h - avoidance	*Macoma bathica* (bivalve)
74.80	low abundance	phoxocephalids
74.80	low abundance	amphipods
81.70	Sediments devoid of feral clams	*Macoma bathica* (bivalve)
89.60	14d LC100	*Nereis virens* (sandworm)
95.80	10d LC67	*Rhepoxynius abronius* (amphipod)
105.00	48h EC93 (abnormal)	bivalve
108.00	EC50	*Photobacterium phosphoreum* (Microtox)
108.00	EC50	*Photobacterium phosphoreum* (Microtox)
111.00	low density	echinoderm
113.00	48h EC23 (abnormal)	oyster
129.00	4wk EC95 (reproduction)	*Tignopus californicus* (bivalve)
129.00	48h LC93	mussel
131.00	10d LC25	*Pennaeus aztecus* (brown shrimp)
137.00	10d LC83	*Leptocheirus plumulsos* (amphipod)
143.00	low richness	benthic
149.00	EC50	*Photobacterium phosphoreum* (Microtox)
160.00	low density	amphipod
160.00	low density	phoxocephalid
167.00	10d LC32	*Ampelisca abdita* (amphipod)
168.00	0.25h EC50 (extract)	*Photobacterium phosphoreum* (Microtox)
169.00	48h EC67 (abnormal)	mussel
171.00	10d LC26	*Rhepoxynius abronius* (amphipod)
172.00	20d LC95	*Leptocheirus plumulsos* (amphipod)
223.00	10d EC63(avoidance)	amphipod
223.00	10d LC95	amphipod
229.00	10d LC62	*Rhepoxynius abronius* (amphipod)
233.00	low density	echinoderm
233.00	low density	*Foraminifera* (sponge)
233.00	low density	*Ophiuroidea* (brittle star)
255.00	10d EC77 (emergence)	*Corophium volutator* (amphipod)
255.00	10d EC69 (emergence)	*Rhepoxynius abronius* (amphipod)
297.00	low richness	macro benthos
297.00	low density	amphipod

Conc. (mg/kg)	Endpoint	Species
297.00	low density	crustacea
297.00	low density	phoxocephalid
312.00	10d LC21	*Rhepoxynius abronius* (amphipod)
312.00	low density	mullosca
314.00	10d LC55	*Hyalella azteca* (amphipod)
321.00	14d reduced growth rate	*Chromadorina germanica* (nematode)
344.00	20d LC37	*Neanthes arenaceodentata* (polychaete)
512.00	48h LC50	*Leiostomus xanthurus* (spot)
512.00	48h LC50	*Fundulus heretoclitus* (mummichog)
570.00	48h EC45 (abnormal)	oyster
613.00	10d LC79	*Rhepoxynius abronius* (amphipod)
840.00	EPA Acute Marine EP Threshold	aquatic biota

MANGANESE

Manganese (Mn) makes up about 0.10% of the earth's crust and is the 12th most abundant element (NAS, 1980). In soil, natural levels of manganese range from 0.6-0.9 mg/kg and its solubility increases with decreasing pH. In surface water, Mn is present at concentrations ranging from 0.001-0.04 mg/L (Rouleau et al., 1995). Manganese oxides and peroxides are used in industry as oxidizers, and elemental Mn is used for manufacturing metal alloys to increase hardness and corrosion resistance. Increasingly, Mn as a Mn carbonyl compound, is being utilized as an anti-knocking agent in engines and is released into the air as Mn_3O_4 following combustion (Brault et al., 1994). Manganese is also present in the air and water discharges from mining and smelting activities (Saric 1986). In living systems, manganese is an essential element that is found most often in the +2 valence state. There is evidence that manganese occurs in surface waters both in suspension in the quadrivalent state and in the trivalent state in a relatively stable, soluble complex (APHA,1989). Manganese is one of the first metals to increase in concentration in acidified waters (Harvey 1983).

Toxicity in Sediment to Benthic Invertebrates. Very little sediment toxicity information is available for manganese. The Ontario Ministry of the Environment has estimated that most benthic organisms in that region will not be adversely affected by concentrations of 460 mg/kg, which is consistent with the Great Lakes pre-colonial sediments background level of 400 mg/kg. A concentration of 1,110 mg/kg manganese is estimated to be toxic to most benthic organisms (Persaud et al., 1990).

Body Mn levels for benthic invertebrates are correlated to the concentration of the metal in the surficial sediments (Bendell-Young and Harvey, 1986).

MERCURY

Mercury (Hg) has no known biological function and is toxic to fish and wildlife. It is a mutagen and carcinogen that adversely affects the central nervous, renal, and reproductive systems of wildlife. Hg occurs in the environment as elemental mercury, Hg_2(II) and Hg(II), the latter of which is naturally oxidized from elemental mercury (Eisler, 1987a). Mercury in ambient waters commonly occurs as mercury (II) or methylmercury. Mercury (II) can be methylated by both aerobic and anaerobic bacteria in the slime coat, liver, and intestines of fish, but methylation apparently does not occur in other tissues or in plants (EPA, 1985-Hg). From a toxicological standpoint, methylmercury (MeHg) poses a greater threat to biota due to its high stability and the ease with which it penetrates membranes in living organisms. Hg(II), however, is more prevalent in aquatic systems, bound up and unavailable in sediment layers. Biota bioconcentrate mercury compounds which can be further biomagnified through food chains (Wren, 1986). High concentrations of mercury in water are often associated with low alkalinity lakes and newly created bodies of water (Weiner and Stokes, 1990). Alkalinity, ascorbic acid, chloride, dissolved oxygen, hardness, organic complexing agents, pH, sediment, and temperature probably affect the acute and chronic toxicity and bioaccumulation of the various forms of mercury.

Anthropogenic sources of Hg include the combustion of fossil fuels, metal mining and processing plants, chloralkali plants, and disposal of batteries and fluorescent lamps (NAS 1978, and Das et al., 1982; as cited in Eisler, 1987a).

Toxicity in Sediment to Benthic Invertebrates. Sediments from the Little Grizzly Creek system in California, which had 0.8 to 3.5 (mean 1.5) mg/kg mercury and an organic carbon content of approximately 1%, caused greater than 90% mortality in *Daphnia magna* and *Hexagenia limbata* (mayfly larva) (Maleug et al., 1984). A Michigan lake sediment in the same study, with an organic carbon content of 2.2% and mercury concentration of 0.29 mg/kg, caused 100% mortality in *D. magna* and 40% mortality in *H. limbata*. However, sediments from the Phillips Chain of Lakes in Wisconsin, with mercury concentrations from 0.8 to 9.4 mg/kg, resulted in less than 20% mortality in both species. These sediments had a high organic carbon content of approximately 15% (studies cited in Long and Morgan, 1991).

Sediments from Waukegan Harbor, Illinois, with a mercury concentration of 0.1 mg/kg resulted in 34% mortality to *Hyalella azteca*. A study of benthic macroinvertebrate communities in Illinois rivers conducted by the Illinois Environmental Protection Agency found that the lowest number of benthic macroinvertebrate taxa occurred at a site with 1.6 mg/kg mercury, while the highest number of taxa occurred at a site with 0.3 mg/kg mercury (studies cited in Long and Morgan, 1991). Long et al., (1995) reported ER-L and ER-M values 0.15 and 0.71 mg/kg. Biological effects were observed in only 42% of the documented studies with concentrations greater than the ER-M (Table 5).

Table 5. Toxicity of mercury to benthic invertebrates in sediment of saline waters (MacDonald et al., 1994).

Conc. (mg/kg)	Endpoint	Species
0.01	48h LC25	*Arbacia punctulata* (sea urchin)
0.01	EPA Chronic Marine EP Threshold	aquatic biota
0.01	10d LC28	*Mysidopsis bahia* (mysid)
0.01	10d LC30	*Streblospio benedicti* (polychaete worm)
0.02	10d LC55	*Hyalella azteca* (amphipod)
0.02	48h EC85 (normal development)	*Arbacia punctulata* (sea urchin)
0.04	96h LC16	*Mysidopsis bahia* (mysid)
0.08	10d LC100	*Corophium volutator* (amphipod)
0.08	10d LC100	*Rhepoxynius abronius* (amphipod)

Conc. (mg/kg)	Endpoint	Species
0.12	1h EC80 (fertilization)	*Arbacia punctulata* (sea urchin)
0.12	low density	annelida
0.14	low density	echinodermata
0.15	low density	arthropods
0.15	10d LC83	*Leptocheirus plumulosus* (amphipod)
0.15	low richness	benthic
0.15	EPA Acute Marine EP Threshold	aquatic biota
0.15	96h LC>50	*Palaemonetes pugio* (shrimp)
0.18	20d LC95	*Leptocheirus plumulosus* (amphipod)
0.18	48h significant increase in burrow time	*Macoma balthica* (bivalve)
0.20	Chronic Marine EqP Threshold	aquatic biota
0.29	10d LC55	*Hyalella azteca* (amphipod)
0.30	10d LC23	amphipod
0.40	20d LC52	*Neanthes sp.* (polychaete)
0.40	10d LC20	*Rhepoxynius abronius* (amphipod)
0.42	Sediments devoid of feral clams	*Mulinia lateralis* (bivalve)
0.46	24h - avoidance	*Mulinia lateralis* (bivalve)
0.47	EC50	*Photobacterium phosphoreum* (Microtox)
0.62	EC50	*Photobacterium phosphoreum* (Microtox)
0.71	48h LC92	mussel
0.89	48h EC68 (abnormal)	mussel
0.90	48h EC59 (abnormal)	bivalve
0.93	EC50	*Photobacterium phosphoreum* (Microtox)
0.95	10d LC67	*Rhepoxynius abronius* (amphipod)
1.09	10d LC62	*Rhepoxynius abronius* (amphipod)
1.44	2d EC60 (abnormal development)	*Dendraster excentricus* (echinoderm)
1.60	48h LC50	*Fundulus heteroclitus* (mummichog)
1.60	48h LC50	*Leiostomus xanthurus* (spot)
1.74	10d LC81	*Rhepoxynius abronius* (amphipod)
2.46	20d LC37	*Neanthes arenaceodentata* (polychaete
3.50	48h EC45 (abnormal)	oyster
11.20	10d LC79	*Rhepoxynius abronius* (amphipod)
11.40	LC10	*Rhepoxynius abronius* (amphipod)
13.10	LC50	*Rhepoxynius abronius* (amphipod)
138.00	1h EC98 (fertilization)	*Arbacia punctulata* (sea urchin)
205.00	EC50	*Photobacterium phosphoreum* (Microtox)
234.00	10d LC32	*Ampelisca abdita* (amphipod)

NICKEL

Nickel is a naturally occuring element that may exist in various mineral forms. It forms 0.008% of the earth's crust (NAS, 1980). Soil and sediment are the primary receptacles for nickel, but mobilization may occur depending on physico-chemical characteristics of the soil. Nickel is used in a wide variety of applications including metallurgical processes and electrical components, such as batteries (ATSDR, 1988; USAF, 1990). There is some evidence that nickel may be an essential trace element for mammals. Nickel occurs in nature in the nonionic and divalent states; other valence states occur very infrequently (Mastromatteo, 1986). Although nickel can exist in several oxidation states, the divalent cation state predominates and is generally considered the most toxic form (EPA 1986-Ni). As with many metals the toxicity of nickel increases as hardness decreases. Fish and invertebrates have approximately the same range of sensitivity.

Toxicity in Sediment to Benthic Invertebrates. No information is available from spiked sediment toxicity tests for nickel; data are only from field studies (Long and Morgan, 1991). In sediments of Lake Union, Washington, 88 mg/kg resulted in 95% mortality of *Hyalella azteca* (Long and Morgan, 1991). Sediments with between 22 and 63 (mean of 40) mg/kg nickel from the Little Grizzly Creek system in California caused greater than 90% mortality in *Daphnia magna* and *Hexagenia limbata* (Maleug et al., 1984). This lake had an organic carbon content of 1%. A Michigan lake sediment in the same study, with an organic carbon content of 2.2% and a nickel concentration of 150 mg/kg, caused 100% mortality in *D. magna* and 40% mortality in *H. limbata*. However, sediments from the Phillips Chain of Lakes in Wisconsin, with a high organic carbon content of approximately 15% and nickel concentrations from 140 to 350 mg/kg, resulted in less than 20% mortality in both species (studies cited in Long and Morgan, 1991).

Long et al., (1995) reported ER-L and ER-M values 20.9 and 51.6 mg/kg. A relatively low percentage (17%) of these documented studies indicated an incidence of biological effects at concentrations greater than the ER-M.

SILVER

Silver (Ag), a basic element, occurs naturally in the environment as a soft, silver colored metal (ATSDR, 1989). It also occurs in a powdery white or dark gray to black compound. Silver is found at an average of 0.1 mg/kg in the earth's crust and about 0.3 mg/kg in soils. Silver metals and silver compounds are used in the production of surgical protheses, fungicides, coinage, jewelry, and dental fillings(Fisher et al., 1984). The accumulation of silver in marine algae appears to result from adsorption rather than uptake; bioconcentration fators of 13,000 - 66,000 have been reported (Fisher et al., 1984; ATSDR, 1989b).

Toxicity in Sediment to Benthic Invertebrates. Effects were not observed in association with silver concentrations less than approximately 0.6 mg/kg (Long and Morgan, 1991). No data were available for freshwater systems. At concentrations of 2.1 to 2.6 mg/kg in marine systems, there was an absence of *Macoma balthica* in Fraser River sediments, low arthropod abundance and low species richness in southern California benthos, and increased burrowing time of *M. balthica* exposed to Strait of Georgia sediments (studies cited in Long and Morgan, 1991) (Table 6).

The ER-L and ER-M values are 1.0 mg/kg and 3.7 mg/kg, respectively. A high percentage (92.8%) of the documented studies in Long et al., (1995) indicated occurence of biological effects at concentrations greater than the ER-M.

Table 6. Toxicity of silver to benthic invertebrates in sediment of saline waters (MacDonald et al., 1994).

Conc. (mg/kg)	Endpoint	Species
0.088	48h LC25	*Arbacia punctulata* (sea urchin)

Conc. (mg/kg)	Endpoint	Species
0.137	48h EC15 (development)	*Arbacia punctulata* (sea urchin)
0.172	1h EC55 (fertilization)	*Arbacia punctulata* (sea urchin)
0.220	LC08	*Mysidopsis bahia* (mysid shrimp)
0.457	1h EC98 (fertilization)	*Arbacia punctulata* (sea urchin)
0.666	EC50	*Photobacterium phosphoreum* (Microtox)
0.812	10d LC32	*Ampelisca abdita* (amphipod)
1.000	24h - avoidance	*Macoma balthica* (bivalve)
1.000	48h EC59 (abnormal)	Bivalve
1.130	0.25h EC50 (extract)	*Photobacterium phosphoreum* (Microtox)
1.700	48h EC56 (abnormal)	Bivalve
1.960	20d LC37	*Neanthes arenaceodentata* (polychaete)
2.100	Sediments devoid of feral clams	*Macoma balthica* (bivalve)
2.200	low abundance	Arthropods
2.250	EC50	*Photobacterium phosphoreum* (Microtox)
2.440	48h EC89 (development)	*Mulinia lateralis* (bivalve)
2.500	low richness	Benthic species
2.600	48h Significant increase in burrowing time	*Macoma balthica* (bivalve)
3.100	low abundance	Echinoderm
3.430	EC50	*Photobacterium phosphoreum* (Microtox)
6.900	48h EC92 (abnormal)	Bivalve
6.900	48h LC92	Mussel
6.900	4wk EC95 (reproduction)	*Tigriopus californicus* (copepod)
8.100	10d LC95	Amphipod
8.100	10d EC37 (avoidance)	Amphipod
8.350	48h EC67 (abnormal)	Mussel

ZINC

Zinc (Zn) is an essential trace element in all organisms; it assures the stability of biological molecules and structures such as DNA, membranes, and ribosomes (Eisler, 1993). It is used commercially primarily in galvanized metals and metal alloys, but zinc compounds also have wide applications as chemical intermediates, catalysts, pigments, vulcanization activators and accelerators in the rubber industry, UV stabilizers, and supplements in animal feeds and fertilizers. Zinc compounds are also used in rayon manufacture, smoke bombs, soldering fluxes, mordants for printing and dyeing, wood preservatives, mildew inhibitors, deodorants, antiseptics, and astringents (Lloyd, 1984; ATSDR, 1989d). Zinc phosphide is used as a rodenticide. Zinc makes up about 0.002% of the earth's crust (NAS, 1980) and occurs in many forms in natural waters and aquatic sediments.

In freshwater with pH >4 and <7, the dominant forms of dissolved zinc are the free ion (aquo ion complex) (98%) and zinc sulfate (2%), whereas at pH 9.0, the dominant forms are the monohydroxide ion (78%), zinc carbonate (16%), and the free ion (6%) (Campbell and Stokes, 1985). Zinc occurs in nature as a sulfide, oxide, or carbonate and background concentrations seldom exceed 0.040 mg/L in water or 200 mg/kg in soil or sediment (Eisler, 1993). It is divalent in solution. Zinc interacts with many chemicals, and it may diminish the toxic effects of cadmium and protect against lead toxicosis in terrestrial animals (Eisler, 1993).

Although it is essential for normal growth and reproduction (Prasad, 1979; Stahl et al., 1989) and important to central nervous system function (Eisler, 1993), the primary toxic effect of zinc is on zinc-dependent enzymes that regulate RNA and DNA. It is most harmful to aquatic life in conditions of low pH, low alkalinity, low dissolved oxygen, and elevated temperature. Zinc is relatively nontoxic in mammals, but excessive intake can cause a variety of effects. It is not known to be carcinogenic by normal exposure routes (Eisler, 1993).

Toxicity in Sediment to Benthic Invertebrates. A concentration of 127 mg/kg caused 34% mortality to *Hyalella azteca* in Waukegan Harbor, Illinois. A concentration of 320 mg/kg in Lake Union, Washington, caused 95% mortality to *H. azteca*. In Torch Lake, Michigan, there was significant mortality of *Daphnia magna* and *Hexagenia limbata* associated with concentrations of 310 mg/kg. At 2 rivers in Illinois, the highest number of benthic macroinvertebrate taxa was associated with concentrations of 96 and 182 mg/kg zinc, while the lowest number of taxa was associated with concentrations of 107 and 327 mg/kg, respectively (studies cited in Long and Morgan, 1991). Long et al., (1995) reported ER-L and ER-M values of 150 and 410 mg/kg for zinc.

INORGANICS

ACENAPHTHENE

Acenaphthene is a polycyclic aromatic hydrocarbon (PAH) compound (EPA-Acen, 1993). Acenaphthene may occur naturally in coal tar or as a by product of various oil and coal tar manufacturing processes (Verschueren, 1983). It is also used in the production of dyes, plastics, insecticides and fungicides.

Toxicity in Sediment to Benthic Organisms. In studies used to calculate the NOAA ER-L, effects were usually observed in association with concentrations of 0.15 mg/kg or greater (Long and Morgan, 1991). The AET for Puget Sound sediments, derived from the Microtox© bioassay, the benthic community composition, oyster larvae bioassay, and *Rhepoxynius abronius* amphipod bioassay, were 0.5, 0.5, 0.5, and 0.63 mg/kg, respectively, in a 1986 study and 0.5, 0.73, 0.5, and 2.0 mg/kg, respectively, in a 1988 study (Long and Morgan, 1991). According to EPA (1993-Acen) benthic organisms represent both the most sensitive and most resistant organisms to acenaphthene in freshwater. The freshwater snail, *Aplexa hypnorum*, was the most resistant having an LC50 >2.04 mg/L and the stonefly, *Peltoperla maria*, was the most sensitive with an LC50 of 0.24 mg/L of acenaphthene. Long et al., (1995) reported ER-L and ER-M values of 16 and 500 mg/kg. The acute and chronic NAWQ criteria for acenaphthene in freshwater are 0.080 and 0.023 mg/L (Suter and Tsao, 1996).

The lowest chronic values for fish, daphnid, and non-daphnid invertebrates in sediment are 5.314, 477.222, and 16.3 mg/kg, respectively (assuming 1% TOC) (Jones et al., 1996).

ACETONE

Toxicity in Sediment to Benthic Organisms. The lowest chronic values (LCV) for fish and daphnids in water are estimated at 507.64 and 1.56 mg/L (Suter and Tsao, 1996) which are equivalent to fish and daphnid LCVs in sediment of 2.968 and 0.00912 mg/kg, respectively (assuming 1% TOC)(Jones et al., 1996).

ANTHRACENE

Anthracene is a member of the polycyclic aromatic hydrocarbons (PAHs) produced by incomplete combustion. Exposure may come from natural (coal tar, volcanoes, and forest fires) or anthropogenic (combustion of fossil fuels, wood burning stoves, furnaces, and power plants) sources.

Toxicity in Sediment to Benthic Invertebrates Long and Morgan (1991) reported an ER-L value of 0.085 mg/kg and an ER-M value of 0.96 mg/kg for the toxicity of anthracene. The ER-L degree of confidence is low because there is no consistency in the effects observed at lower concentrations. The AET for Puget Sound sediments, derived from the Microtox© bioassay, the benthic community composition, oyster larvae bioassay, and *Rhepoxynius abronius* amphipod bioassay, were 0.96, 1.3, 0.96, and 1.9 mg/kg, respectively, in a 1986 study and 0.96, 4.4, 0.96, and 13.0 mg/kg, respectively, in a 1988 study (Long and Morgan, 1991). Long et al., (1995) reported ER-L and ER-M values of 85.3 and 1100 mg/kg. There are no SQC or NAWQ criteria for anthracene, however, the SQB value derived using equilibrium partitioning, based on the Tier II SCV, and assuming 1% organic carbon is 0.0003 mg/kg (Jones et al., 1996). The freshwater SCV for anthracene is 0.218 mg/L (Suter and Tsao, 1996). The SQB derived from the LCV for fish is 0.023672 mg/kg.

BENZO(A)ANTHRACENE

Benzo(a)anthracene (B(a)A) is a polycyclic aromatic hydrocarbon (PAH) compound. B(a)A is found in smoke and soot from the burning of gasoline, garbage, or any animal or plant material (ATSDR, 1990b). It is also found in coal tar pitch that industries use to join electrical parts or in creosote, used to preserve wood. B(a)A is a known animal carcinogen (ATSDR, 1990b)

Toxicity in Sediment to Benthic Organisms In bioassays of the lower Columbia River sediments, no toxicity to *Hyalella azteca* was observed at concentrations of 2.2 mg/kg. However, these data were not used in the calculation of the ER-L (Long and Morgan, 1991). In the studies used to calculate the ER-L, no effects were observed at concentrations below 0.06 mg/kg. The overall AET from these data was 0.55 mg/kg, although AET values in the data base ranged from 1.3 to 5.1 mg/kg for Puget Sound to 0.06 to 1.1 mg/kg for San Francisco Bay. Long et al., (1995) reported ER-L and ER-M values of 261 and 1600 mg/kg. There are no SQC for benzo(a)anthracene, however, the SQB derived using equilibrium partitioning and assuming 1% organic carbon is 0.109 mg/kg and is based on the Tier II SCV (Jones et al., 1996). The freshwater SCV is 0.000027 mg/L (Suter and Tsao, 1996). The SQB derived from the LCV for Daphnids is 2.59 mg/kg.

BENZO(A)PYRENE

Benzo(a)pyrene (BaP) is a polycyclic aromatic hydrocarbon (PAH) consisting of 5 fused benzene rings. Despite their high lipid solubility, most PAH's show little tendency to biomagnify in food chains, probably because they are rapidly metabolized in most biota (Eisler, 1987b). PAH's are ubiquitous in nature, produced by forest fires, microbial synthesis, and anthropogenic activities. PAH's are teratogenic, mutagenic, and carcinogenic, with the higher molecular weight compounds being less toxic than lighter compounds (Eisler, 1987b).

Toxicity in Sediment to Benthic Organisms A study was found relating effects data in freshwater sediment to concentrations of benzo(a)pyrene: 220 mg/kg resulted in 95% mortality of *Hyallela azteca*. In the studies documented in Long et al. (1995), 63% indicated biological effects at concentrations between the ER-L (430 mg/kg) and ER-M (1600 mg/kg), and 80% of the studies at concentrations above the ER-M indicated biological effects. The freshwater SCV for benzo(a)pyrene is 0.000014 mg/L (Suter and Tsao, 1996). There are no SQC for benzo(a)pyrene, however, the SQB derived using equilibrium partitioning and assuming 1% organic carbon is 0.14 mg/kg and is based on the Tier II SCV (Jones et al., 1996) The SQB derived from the LCV for Daphnids is 3.0 mg/kg.

ALPHA-BHC

Toxicity in Sediment to Benthic Organisms. The lowest chronic values (LCV) for daphnids is estimated at 0.0095 and 1.56 mg/L (Suter and Tsao, 1996) which is equivalent to a daphnid LCV in sediment of 5.199 mg/kg (assuming 1% TOC) (Jones et al., 1996).

BIS(2-ETHYLHEXYL)PHTHALATE

Bis(2-ethylhexyl)phthalate (BEHP) or di(2-ethylhexyl)phthalate is a colorless oily liquid that is extensively used as a plasticizer in a wide variety of industrial, domestic and medical products. The wide-spread uses of bis(2-ethylhexyl)phthalate have made the compound, along with other phthalic acid esters, ubiquitous in the environment. It has been detected in ground water, surface water, drinking water, air, soil, plants, fish and animals (Sittig, 1985; Sandmeyer and Kirwin, 1978). While bioaccumulation factors for bis(2-ethylhexyl)phthalate at lower trophic levels are high, because it is rapidly metabolized, levels in higher trophic levels are generally lower than those observed at lower trophic levels (Peakall, 1975).

Toxicity in Sediment to Benthic Organisms There were no specific data found relating to the toxicity of BEHP to benthic organisms. There are no SQC available, however, the SQB derived using equilibrium partitioning, based on the Tier II SCV, and assuming 1% organic carbon is 8.9E+05 mg/kg. (Jones et al., 1996). The freshwater SCV for BEHP is 0.03 mg/L (Suter and Tsao, 1996). The SQB derived from the LCV for Daphnids is 82,626.861 mg/kg.

2- BUTANONE

The lowest chronic values (LCV) for fish and daphnids in water are estimated at 282.17 and 1,394.93 mg/L (Suter and Tsao, 1996) which are equivalent to fish and daphnid LCVs in sediment of 5.475 and 27.066 mg/kg, respectively (assuming 1% TOC)(Jones et al., 1996).

CARBON DISULFIDE

Toxicity in Water to Aquatic Life. The EC50 for *Daphnia magna* is 2.1 mg/L and the LC50 for mosquitofish is 135 mg/L (Van Leeuwen et al. 1985, AQUIRE). The secondary chronic value (Suter and Tsao, 1996) of 0.00092 mg/L is used as the water quality benchmark.

CHRYSENE

Chrysene is a polycyclic aromatic hydrocarbon (PAH) compound and like all other PAH compounds it is derived from both natural and man-made sources. The major sources of chrysene released into the environment are from the incomplete combustion of carbonaceous material, residential heating and open burning (ATSDR, 1990c). Chrysene is known to accumulate in aquatic biota, however, detected concentrations are low because many organisms metabolize and excrete PAH compounds rapidly (ATSDR, 1990c).

Toxicity in Sediment to Benthic Organisms. In freshwater systems, a concentration of 4.1 mg/kg was not toxic to *Hyalella azteca* in the Columbia River but a concentration of 170 mg/kg in Lake Union, Washington, resulted in 95% mortality to *Hyalella azteca*. In the studies used to calculate the ER-L, effects were almost always observed at concentrations exceeding 0.9 mg/kg, although the lowest Puget Sound and San Francisco Bay AET values were 1.4 and 1.7 mg/kg, respectively (studies cited in Long and Morgan, 1991). Long et al., (1995) reported ER-L and ER-M values of 384 and 2800 mg/kg. There are no SQC or SQB values available for chrysene.

DI-N-BUTYL PHTHALATE

Toxicity in Sediment to Benthic Organisms. The lowest chronic values (LCV) for fish and daphnids in water are calculated at 0.717 and 0.697 mg/L (Suter and Tsao, 1996) which are equivalent to LCVs in sediment of 254.442 and 238.596 mg/kg, respectively (assuming 1% TOC) (Jones et al., 1996).

DIBENZ(A,H)ANTHRACENE

Dibenz(a,h)anthracene (DB(a,h)A) is a polycyclic aromatic hydrocarbon (PAH) compound. Like all other PAH compounds, it is a product of combustion and it's major fate is most likely sorption and biodegradation (ATSDR, 1990d). The half-life of (DB(a,h)A) in soil is estimated at 750 days.

Toxicity in Sediment to Benthic Organisms In studies used to calculate the ER-L, effects in sediments were observed at concentrations as low as 0.042 mg/kg in marine systems (Long and Morgan, 1991). The safe sediment level based upon equilibrium partitioning and the acute NAWQ criteria is 240 mg/kg (Long and Morgan, 1991). Long et al., (1995) reported ER-L and ER-M values of 63.4 and 260 mg/kg. There are no SQC or SQB for dibenz(a,h)anthracene.

DIBENZOFURAN

Toxicity in Sediment to Benthic Organisms. The lowest chronic value (LCV) for daphnids is estimated at 1.003 mg/L (Suter and Tsao, 1996) which is equivalent to an LCV in sediment of 113.256 mg/kg (assuming 1% TOC) (Jones et al., 1996).

1,1- DICHLOROETHANE

Toxicity in Sediment to Benthic Organisms. The lowest chronic value (LCV) for fish is estimated at 14.68 mg/L (Suter and Tsao, 1996) which is equivalent to an LCV in sediment of 8.494 mg/kg (assuming 1% TOC) (Jones et al., 1996).

1,2- DICHLOROETHYLENE

Dichloroethylenes are clear, colorless liquids and consist of three isomers: 1,1-dichloroethylene (1,1-DCE), cis-1,2-DCE, and trans 1,2-DCE (EPA 1980d). DCE is the isomer most widely used in industry and, consequently, in aquatic toxicity tests. DCE is used in the production of copolymers, such as Saran, which are used in the packaging industry and as coatings for steel pipes, and the interior of fuel storage tanks. 1,1-DCE is not known to occur in nature and is expected to be short-lived in water because of its volatilization to the atmosphere.

Toxicity in Sediment to Benthic Organisms. The lowest chronic value (LCV) for fish in water is estimated at 9.538 mg/L (Suter and Tsao, 1996) which is equivalent to an LCV in sediment of 6.466 mg/kg (assuming 1% TOC) (Jones et al., 1996).

DDT, Total

DDT (1,1,1-trichloro-2,2-bis(p-chlorophenyl)ethane) is an organochlorine insecticide that was banned from use in the United States in 1972. DDT, and its metabolites, DDE and DDD, are highly persistent man-made chemicals and are not known to occur naturally in the environment (ATSDR, 1992). The half-life of DDT in soil is reported to range from 2 to 15 years (ATSDR, 1993). DDT and it's metabolites are also highly lipophilic and have a high bioaccumulation potential. A bioconcentration factor for rainbow trout is reported to be 12000 (ATSDR, 1993). DDT's are transported from one medium to another by solubilization, adsorption, bioaccumulation, or volatilization (ATSDR, 1992).

4,4' - DDT

Toxicity in Sediment to Benthic Organisms Long et al., (1995) reported ER-L and ER-M values of 1.58 mg/kg and 46.1 mg/kg for total DDT. There are no SQC for DDT, however, the SQB derived using the equilibrium partitioning and assuming 1% carbon is 0.343 mg/kg and is based on the NAWQ criteria (Jones et al., 1996). The freshwater NAWQ criteria for DDT is 0.0011 mg/L (Suter and Tsao, 1996). The SQB derived from the LCV for plants is 5.58626 mg/kg.

DIETHYL PHTHALATE

Toxicity in Sediment to Benthic Organisms. The secondary chronic value (SCV) for fish in water is estimated at 0.21 mg/L (Suter and Tsao, 1996) which is equivalent to an SCV in sediment of 0.606 mg/kg (assuming 1% TOC) (Jones et al., 1996).

ENDOSULFAN

Toxicity in Sediment to Benthic Organisms. The secondary chronic value (SCV) for fish in water is estimated at 0.000051 mg/L (Suter and Tsao, 1996) which is equivalent to an SCV in sediment of 0.0055 mg/kg (assuming 1% TOC) (Jones et al., 1996).

FLUORANTHENE

Fluoranthene is a member of the polycyclic aromatic hydrocarbon (PAH) group of organic compounds. Sources of fluoranthene include crude oil, coal tar and motor oil or it may be produced by plants, algae and bacteria (Verschueren, 1983; as cited in EPA, 1993-Flu). Gradual increases in fossil fuel consumption in the United States will lead to increases in emissions of PAH's to the environment. The impact of PAH's is of environmental concern because they are known carcinogens and/or mutagens. Although fluoranthene bioaccumulates in aquatic biota, the associated health or ecological risks are unknown (EPA, 1993-Flu).

Toxicity in Sediment to Benthic Organisms In Lake Union, Washington, sediment with a concentration of 570 mg/kg caused 95% mortality to *Hyalella azteca*. Columbia River, Washington, sediment with 2.1 mg/kg fluoranthene was not toxic to *Hyalella azteca*. The lowest AET for Puget Sound and San Francisco Bay were 1.7 and 2.0 mg/kg, respectively. The confidence in the ER-L is high (Long and Morgan, 1991). The EPA freshwater SQC assuming 1% organic carbon is 6.2 mg/kg (EPA, 1993-Flu).

A freshwater sediment with approximately 0.5% organic carbon was spiked with fluoranthene to generate an EC50 for *Hyalella azteca* and *Chironomus tentans*, using organism immobility as the endpoint (Suedel et al., 1993). The EC50 values were between 2.3 and 7.4 mg/kg for *H. azteca* and between 3.0 and 8.7 mg/kg for *C. tentans*. The SQC for fluoranthene derived using equilibrium partitioning and assuming 1% organic carbon is 6.2 mg/kg (EPA, 1993-Flu).

FLUORENE

Fluorene is a polycyclic aromatic hydrocarbon (PAH) compound. Like all other PAH compounds, fluorene is the result of the combustion of fossil fuels and remains persistent in the environment (Eisler, 1987). Fluorene compounds may be introduced into aquatic environments by sewage effluents, surface runoff, or petroleum spills. PAH compounds reach soil by direct deposition or by deposition on vegetation.

Toxicity in Sediment to Benthic Organisms In Lake Union, Washington, sediment with a concentration of 40 mg/kg fluorene caused 95% mortality in *Hyalella azteca*. The SQC calculated using equilibrium partitioning and the acute NAWQ criteria and 1% organic carbon yields a value of 7.0 mg/kg (Long and Morgan, 1991). Long et al, (1995) reported ER-L and ER-M values of 19 and 540 mg/kg for fluorene.

METHYLENE CHLORIDE

Toxicity in Sediment to Benthic Organisms. The lowest chronic values (LCV) for fish and daphnids in water are calculated at 108.0 and 42.667 mg/L (Suter and Tsao, 1996) which are equivalent to LCVs in sediment of 18.407 and 7.272 mg/kg, respectively (assuming 1% TOC) (Jones et al., 1996).

2-METHYLNAPHTHALENE

Toxicity in Sediment to Benthic Organisms. The lowest AET values for 2-methylnaphthalene in San Francisco Bay and Puget Sound were 0.000027 mg/kg and 0.000045 mg/kg, respectively. Sediment in Commencement Bay, WA was highly toxic to amphipods at 0.000546 mg/kg 2-methylnaphthalene (MacDonald et al., 1994).

4-METHYLPHENOL

Toxicity in Sediment to Benthic Organisms. The lowest chronic values (LCV) for fish and daphnids in water are estimated at 0.489 and 1.316 mg/L (Suter and Tsao, 1996) which are equivalent to LCVs in sediment of 0.445 and 1.197 mg/kg, respectively (assuming 1% TOC) (Jones et al., 1996).

NAPHTHALENE

Naphthalene is a white solid substance used in the manufacture of dyes, resins and in mothballs. It is released to the air from the burning of coal and oil and from the use of mothballs containing naphthalene. Naphthalene may also be released into the air by coal tar production and wood preservation. In water and soil, naphthalene is either destroyed by bacteria or evaporated into the air within a few hours or days (ATSDR, 1989a). Naphthalene breaks down readily in the environment and is easily metabolized by various organisms (ATSDR, 1989a).

Toxicity in Sediment to Benthic Organisms In Lake Union, Washington, sediments with 40 mg/kg naphthalene caused 95% mortality in *Hyalella azteca.* Effects were almost always observed at concentrations greater than 0.50 mg/kg in marine systems (Long and Morgan, 1991). The Puget Sound AET was 2.1 mg/kg. Long et al., (1995) reported ER-L and ER-M values of 160 and 2100 mg/kg. The SQB value is 0.242 mg/kg and is derived from equilibrium partitioning and assuming 1% organic carbon (Jones et al., 1996). The freshwater SCV is 0.012 mg/L (Suter and Tsao, 1996). The SQB derived from the LCV for fish is 10.77 mg/kg.

PAHs, TOTAL

Polycyclic aromatic hydrocarbons (PAH) are composed of two or more fused aromatic rings containing only carbon and hydrogen atoms (Hodgson, 1984). Anthropogenic combustion of fossil fuels is thought to be the primary source of PAH in the aquatic environment. Some PAH's are among the most potent carcinogens known to exist (Eisler, 1987b). Prior to 1900, the production and degradation of PAH's was balanced, however, the recent increase in industrial development and increased emphasis of fossil fuels as energy sources has disrupted that balance. PAH's reaching the sediment may be adsorbed or assimilated by plant leaves before entering the animal food chain. The fate of PAH's that accumulate in sediments is thought to biotransformation and biodegradation by benthic organisms (Eisler, 1987b). Long et al., (1995) reported ER-L and ER-M values of 4022 and 44792 mg/kg for total PAH.

PCBs

Polychlorinated biphenyls (PCB's) are a family of man-made chemicals consisting of 209 individual compounds with varying toxicity (ATSDR, 1989c). Aroclor is the trade name for PCB's made by Monsanto. Because of their insulating and nonflammable properties, PCB's were widely used in industrial applications such as coolants and lubricants in transformers, capacitors, and electrical equipment (ATSDR, 1989c). The United States stopped manufacturing PCB's in 1977 due to evidence that they accumulated in the environment. Although PCB's are no longer manufactured or used in the United States, they remain present and will continue to become a widespread environmental contaminant. The biodegradation of PCB's in soil is slow, especially in soils with high organic carbon content (ATSDR, 1993).

PCB-1248

Toxicity in Sediment to Benthic Organisms. The log K_{oc} for Aroclor 1248 is 7.02. The sediment quality benchmark (SQB) of 1.05 mg/kg is derived using the equilibrium partitioning approach based on 1% organic carbon. The secondary chronic value (Suter and Tsao, 1996) of 0.00008 mg/L is used as the water quality benchmark. The secondary chronic value implies a greater than 20% chance that the NAWQC, if its value were known, would be exceeded. For comparison, substitution of the lowest chronic value for daphnids results in a SQB of 450 mg/kg for Aroclor 1248.

PCB-1254

Toxicity in Sediment to Benthic Organisms The log K_{oc} for Aroclor 1254 is 5.93. There are no SQC for PCB-1254, however, the SQB derived from equilibrium partitioning and assuming

1% organic carbon is 0.814 mg/kg (Jones et al., 1996). The freshwater SCV is 0.000033 mg/kg (Suter and Tsao, 1996). The SQB derived from the LCV for plants is 0.85 mg/kg.

PCB-1260

Toxicity in Sediment to Benthic Organisms The log K_{oc} for Aroclor 1260 is 7.02. There are no SQC for PCB-1260, however, the SQB derived from the equilibrium partitioning and assuming 1% organic carbon is 4574 mg/kg (Jones et al., 1996). The freshwater SCV is 0.094 mg/L (Suter and Tsao, 1996). The SQB derived from the LCV for fish is 136.127 mg/kg.

PHENANTHRENE

Phenanthrene is a polycyclic aromatic hydrocarbon (PAH) compound. It is produced by fractional distillation of high-boiling coal-tar oil and purification of the crystalline solid (EPA, 1993-Phen). Phenanthrene may be used in the manufacturing of dye, drugs, and explosives. The fate of phenanthrene in sediment is highly influenced by sorption and biodegradation. Phenanthrene has the ability to bioaccumulate in aquatic biota. The acute toxicity of phenanthrene in freshwater ranges from 0.096 to >1.150 mg/L and 0.0219 to 0.6 mg/L for saltwater organisms.

Toxicity in Sediment to Benthic Organisms In Lake Union, Washington, sediments with 410 mg/kg phenanthrene caused 95% mortality among *Hyalella azteca.* Columbia River, Washington, sediments with 0.58 mg/kg phenanthrene were not toxic to the same species (studies cited in Long and Morgan, 1991). The EPA SQC for phenanthrene is 1.8 mg/kg assuming 1% organic carbon (EPA, 1993-Phen). Long et al., (1995) reported ER-L and ER-M values of 240 and 1500 mg/kg. The SQC for phenanthrene derived using equilibrium partitioning and assuming 1% organic carbon is 1.8 mg/kg (EPA, 1993-Phen).

PHENOL

Toxicity in Sediment to Benthic Organisms. The lowest chronic values (LCV) for fish and daphnids in water are calculated at <0.2 and 2.005 mg/L (Suter and Tsao, 1996) which are equivalent to LCVs in sediment of <0.0574 and 0.575 mg/kg, respectively (assuming 1% TOC) (Jones et al., 1996).

PYRENE

Pyrene is an polycyclic aromatic hydrocarbon (PAH) compound. The PAH are of environmental concern because they are known carcinogens and/or mutagens. Like all other PAH compounds, pyrene is a product of combustion and it's major fate is most likely biodegradation (ATSDR, 1990a).

Toxicity in Sediment to Benthic Organisms In Lake Union, Washington, sediments with 750 mg/kg pyrene caused 95% mortality among *Hyalella azteca.* A concentration of 2.5 mg/kg in Columbia River, Washington, sediments was not toxic to the same species (studies cited in Long and Morgan, 1991). The EPA interim SQC based on equilibrium partitioning and 1% organic carbon is 13.1 mg/kg (Long and Morgan, 1991). Long et al., (1995) reported ER-L and ER-M values of 665 and 2600 mg/kg.

TOLUENE

Toxicity in Sediment to Benthic Organisms. The lowest chronic values (LCV) for fish and daphnids in water are calculated at 1.269 and 25.229 mg/L (Suter and Tsao, 1996) which are equivalent to LCVs in sediment of 6.449 and 128.218 mg/kg, respectively (assuming 1% TOC) (Jones et al., 1996).

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