

Copper: Adverse Effects on Salmonids

Scientific Abstracts and References

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The following information was collected from recent peer reviewed scientific publications. The full text of each article is available from the journal and publisher cited. Cu = copper. * Indicates annotations by C. Woody for clarification or explanation. Questions or comments or criticisms greatly appreciated. For information on the importance of olfaction to fish see the Salmon Ecology 101 Fact Sheet.

Pyle, GG, and RS Mirza. 2007. Copper-impaired chemosensory function and behavior in aquatic animals. Human and Ecological Risk Assessment. 13 (3): 492 – 505.

Abstract: Chemosensation is one of the oldest and most important sensory modalities utilized by aquatic animals to provide information about the location of predators, location of prey, sexual status of potential mates, genetic relatedness of kin, and migratory routes, among many other essential processes. The impressive sophistication of chemical communication systems among aquatic animals probably evolved because of the selective pressures exerted by water as a "universal solvent." Impairment of chemosensation by toxicants at the molecular or cellular level can potentially lead to major perturbations at higher levels of biological organization. We have examined the consequences of metal-impaired chemosensory function in a range of aquatic animals that represents several levels of a typical aquatic ecosystem. In each case, low, environmentally relevant metal concentrations were sufficient to cause chemosensory dysfunction. Because the underlying molecular signal transduction machinery of chemosensory systems demonstrates a high degree of phylogenetic conservation, we speculate that metal-impaired chemosensation among phylogenetically disparate animal groups probably results from a common mechanism of impairment. We propose developing a chronic chemosensory-based biotic ligand model (BLM) that maintains the advantages of the current BLM approach, while simultaneously overcoming known difficulties of the current gill-based approach and increasing the ecological relevance of current BLM predictions.

'Safe' heavy metals hit fish senses. 18:16 09 April 2007. NewScientist.com news service. Aria Pearson

Pollution far below the level seen as dangerous for aquatic life has nevertheless dramatically altered animal behaviour in North American lakes. Heavy metals are knocking out the sense of smell in organisms from bacteria to fish. Even we may not be immune.

Nathaniel Scholz, at the Northwest Fisheries Science Center in Seattle, Washington, and colleagues found that **salmon lose their sense of smell if there are even low levels of copper in the water** they are swimming

in. The fish could die as a result, because they cannot smell chemicals that would warn of a nearby predator.

All over the world, storm water run-off shuttles heavy metals such as copper and zinc from industry, mines and built-up areas into natural water courses. The concentrations are generally low - too low for polluters to bother about, or so many of them seem to have thought. "Now we're going after [this] 'So what?' question," says Scholz.

Scholz's team kept young coho salmon in tanks with different concentrations of copper for 3 hours, then measured their movements when a drop of salmon skin extract was added to the water. In the wild, the skin would be a cue that a predator may have injured a fish nearby.

Unexposed salmon stopped swimming, sank to the bottom of the tank and kept still - typical tactics for avoiding predators. But fish exposed to concentrations of copper as low as 2 parts per billion (ppb) just stopped for a few seconds, or merely slowed down, while fish exposed to 10 or more ppb didn't notice the cue at all (*Environmental Science and Technology*, DOI: 10.1021/es062287r).

The US Environmental Protection Agency has set the maximum safe level of copper for aquatic life at 13 parts per billion, well above that needed to wipe out the salmon's ability to sense chemical cues. Yet Greg Pyle, at Nipissing University in North Bay, Ontario, Canada, has found chemosensory problems at three levels of the food chain at or below 5 ppb, the limit set by Ontario's water quality standards. "The phenomenon is ubiquitous," he says.

Leeches lost their ability to smell food, zooplankton were unable to evade predators, and fathead minnows couldn't recognize their eggs: the fish ate them instead of protecting them. The contamination in these lakes is much too weak to kill these organisms outright, Pyle says, yet their populations are suffering.

Metals may have the same effect in humans. The makers of the cold remedy Zicam, which contains zinc, recently settled out of court for \$12 million with people who reported losing their sense of smell after spraying the product into their noses. The company maintains the remedy is safe. Studies have not been conducted to test whether zinc destroys human sensory abilities, but given what's happening in aquatic ecosystems, Pyle believes it could. "Don't squirt metals up your nose," he says. "That would be my advice".

Sandahl, JF, DH Baldwin, JJ Jenkins and NL Schlotz. 2007. A sensory system at the interface between urban stormwater runoff and salmon survival. *Environ. Sci. Technol.* 41:2998-3004.

Abstract: Motor vehicles are a major source of toxic contaminants such as copper, a metal that originates from vehicle exhaust and brake pad wear. Copper and other pollutants are deposited on roads and other impervious surfaces and then transported to aquatic habitats via stormwater runoff. In the western United States, exposure to non-point source pollutants such as copper is an emerging concern for many populations of threatened and endangered Pacific salmon (*Oncorhynchus spp.*) that spawn and rear in coastal watersheds and estuaries. To address this concern, we used conventional neurophysiological recordings to investigate the impact of ecologically relevant copper exposures (0-20 $\mu\text{g/L}$ for 3 h) on the olfactory system of juvenile coho salmon (*O. kisutch*). These recordings were combined with computer-assisted video analyses of behavior to evaluate the sensitivity and responsiveness of copper-exposed coho to a chemical predation cue (conspecific alarm pheromone). The sensory physiology and predator avoidance behaviors of juvenile coho were both significantly impaired by copper at concentrations as low as 2 $\mu\text{g/L}$. Therefore, copper-containing stormwater runoff from urban landscapes has the potential to cause chemosensory deprivation and increased predation mortality in exposed salmon.

Baldwin, DH, JF Sandahl, JS Labenia, and NL Schloz. 2003. Sublethal effects of copper on coho salmon: impacts on nonoverlapping

receptor pathways in the peripheral olfactory nervous system. Environmental Toxicology and Chemistry. 10:2266–2274.

Abstract: The sublethal effects of copper on the sensory physiology of juvenile coho salmon (*Oncorhynchus kisutch*) were evaluated. In vivo field potential recordings from the olfactory epithelium (electro-olfactograms) were used to measure the impacts of copper on the responses of olfactory receptor neurons to natural odorants (L-serine and taurocholic acid) and an odorant mixture (L-arginine, L-aspartic acid, L-leucine, and L-serine) over a range of stimulus concentrations. Increases in copper impaired the neurophysiological response to all odorants within 10 min of exposure. The inhibitory effects of copper (1.0–20.0 mg/L) were dose dependent and they were not influenced by water hardness. Toxicity thresholds for the different receptor pathways were determined by using the benchmark dose method and found to be similar (a 2.3–3.0 mg/L increase in total dissolved copper over background). Collectively, examination of these data indicates that copper is broadly toxic to the salmon olfactory nervous system. Consequently, short-term influxes of copper to surface waters may interfere with olfactory-mediated behaviors that are critical for the survival and migratory success of wild salmonids.

Hansen, JA, JD Rose, RA Jenkins, KG Gerow, HL Bergman. 1999. Chinook salmon (*Oncorhynchus tshawytscha*) and rainbow trout (*Oncorhynchus mykiss*) exposed to copper: neurophysiological and histological effects on the olfactory system. Environmental Toxicology and Chemistry. 9:1979-1991.

Abstract: Olfactory epithelial structure and olfactory bulb neurophysiological responses were measured in chinook salmon and rainbow trout in response to 25 to 300 µg copper (Cu)/L. Using confocal laser scanning microscopy, the number of olfactory receptors was significantly reduced in chinook salmon exposed to greater than or equal to 50 µg Cu/L and in rainbow trout exposed to greater than or equal to 200 µg Cu/L for 1 h. The number of receptors was significantly reduced in both species following exposure to 25 µg Cu/L for 4 h. Transmission electron microscopy of olfactory epithelial tissue indicated that the loss of receptors was from cellular necrosis. Olfactory bulb electroencephalogram (EEG) responses to 10(-3) M L-serine were initially reduced by all Cu concentrations but were virtually eliminated in chinook salmon exposed to greater than or equal to 50 µg Cu/L and in rainbow trout exposed to greater than or equal to 200 µg Cu/L within 1 h of exposure. Following Cu exposure, EEG response recovery rates were slower in fish exposed to higher Cu concentrations. The higher sensitivity of the chinook salmon Olfactory system to Cu-induced histological damage and neurophysiological impairment parallels the relative species sensitivity observed in behavioral avoidance experiments. This difference in species sensitivity may reduce the survival and reproductive potential of chinook salmon compared with that of rainbow trout in Cu-contaminated waters.

Dethloff, GM, D Schlenk, JT Hamm, and HC Bailey. 1999. Alterations in physiological parameters of rainbow trout (*Oncorhynchus mykiss*) with exposure to copper and copper/zinc mixtures. Ecotoxicology and Environmental Safety. 42(3):253-264.

Abstract: Rainbow trout (*Oncorhynchus mykiss*) were exposed to sublethal concentrations of copper (Cu, 14 µg/liter or parts per billion) and zinc (Zn, 57 and 81 µg/liter or ppb) for a 21-day period. The four treatments included a control, a Cu control, a Cu and low-Zn treatment and a Cu and high-Zn treatment. Selected parameters [e.g., hemoglobin (Hb), hematocrit (Hct), plasma glucose, lactate and cortisol, differential leukocyte count, respiratory burst, tissue metal concentrations, hepatic metallothionein (MT), brain acetylcholinesterase (AChE)] were evaluated at 2, 7, 14, and 21 days of exposure. Whole blood and

plasma parameters were not altered by exposure to metals. The percentage of lymphocytes was consistently decreased in the three metal treatments, while percentages of neutrophils and monocytes were increased. Respiratory burst activity was elevated in all metal treatments. Gill Zn concentration was highly variable, with no significant alterations occurring. Gill Cu concentration was elevated above control levels in all metal treatments, Gill Cu concentration in the two Cu/Zn treatments was also elevated above levels in the Cu control. Hepatic metal concentrations and MT levels were not altered from control values. Measurements of brain AChE indicated an elevation in this parameter across metal treatments. In general, alterations in physiological parameters appeared to be due to Cu, with Zn having no interactive effect.

Hansen JA, Lipton J, Welsh PG. 2002. Environmental toxicology and chemistry. 21 (3): 633-639.

Abstract: Bull trout (*Salvelinus confluentus*) were recently listed as threatened in the United States under the federal Endangered Species Act. Past and present habitat for this species includes waterways contaminated with heavy metals released from mining activities. Because the sensitivity of this species to copper was previously unknown, we conducted acute copper toxicity tests with bull (*bull trout are an endangered type of charr like Dolly Varden) and rainbow trout (*Oncorhynchus mykiss*) in side-by-side comparison tests. Bioassays were conducted using water at two temperatures (8 degrees C and 16 degrees C) and two hardness levels (100 and 220 mg/L as CaCO₃). At a water hardness of 100 mg/L both species were less sensitive to copper when tested at 16 degrees C compared to 8 degrees C. The two species had similar sensitivity to copper in 100-mg/L hardness water, but bull trout were 2.5 to 4 times less sensitive than rainbow trout in 220-mg/L hardness water. However, when our results were viewed in the context of the broader literature on rainbow trout sensitivity to copper, the sensitivities of the two species appeared similar. This suggests that adoption of toxicity thresholds that are protective of rainbow trout would be protective of bull trout; however, an additional safety factor may be warranted because of the additional level of protection necessary for this federally threatened species.

Brix KV, DeForest DK, Adams WJ. 2001. Assessing acute and chronic copper risks to freshwater aquatic life using species sensitivity distributions for different taxonomic groups. Environmental Toxicology and Chemistry. 20 (8): 1846-1856.

Abstract: Using copper as an example, we present a method for assessing chemical risks to an aquatic community using species sensitivity distributions (SSDs) for different taxonomic groups. This method fits probability models to chemical exposure and effects data to estimate the percentage of aquatic species potentially at risk and expands on existing probabilistic risk assessment methodologies. Due to a paucity of chronic toxicity data for many chemicals, this methodology typically uses an acute-chronic ratio (ACR) to estimate the chronic effects distribution from the acute effects distribution. We expanded on existing methods in two ways. First, copper SSDs were developed for different organism groups (e.g., insects, fish) that share similar sensitivities or ecological functions. Integration of exposure and effects distributions provides an estimate of which organism groups may be at risk. These results were then compared with a site-specific food web, allowing an estimation of whether key food web components are potentially at risk and whether the overall aquatic community may be at risk from the perspective of ecosystem function. Second, chronic SSDs were estimated using the relationship between copper ACRs and acute toxicity (i.e., the less acutely sensitive a species, the larger the ACR). This correction in the ACR removes concerns previously identified with use of the ACR and allows evaluation of a significantly expanded chronic data set with the same approach as that for assessing acute risks.

Goldstein, JN, DF Woodward, and AM Farag. 1999. Movement of adult Chinook salmon during spawning migration in a metals-contaminated system, Coeur d'Alene River, Idaho. *Transactions of the American Fisheries Society* 128:121–129.

Abstract: Spawning migration of adult male chinook salmon *Oncorhynchus tshawytscha* was monitored by radio telemetry to determine their response to the presence of metals contamination in the South Fork of the Coeur d'Alene River, Idaho. The North Fork of the Coeur d'Alene River is relatively free of metals contamination and was used as a control. In all, 45 chinook salmon were transported from their natal stream, Wolf Lodge Creek, tagged with radio transmitters, and released in the Coeur d'Alene River 2 km downstream of the confluence of the South Fork and the North Fork of the Coeur d'Alene River. Fixed telemetry receivers were used to monitor the upstream movement of the tagged chinook salmon through the confluence area for 3 weeks after release. During this period, general water quality and metals concentrations were monitored in the study area. Of the 23 chinook salmon observed to move upstream from the release site and through the confluence area, the majority (16 fish, 70%) moved up the North Fork, and moved up the North Fork, and only 7 fish (30%) moved up the South Fork, where greater metals concentrations were observed. Our results agree with laboratory findings and suggest that natural fish populations will avoid tributaries with high metals contamination.

Dethloff, GM, and HC Bailey. 1998. Effects of Copper on Immune System Parameters of Rainbow Trout (*Oncorhynchus mykiss*). *Environmental Toxicology and Chemistry*. 17(9):1807-1814.

Abstract: Agricultural, urban, industrial, and mining sources release metals into waterways. The effects of sublethal concentrations of metals on integrated physiological processes in fish, such as immunocompetency, are not well understood. The objective of this study was to determine the physiological effects of a range of sublethal copper concentrations (6.4, 16.0, and 26.9 $\mu\text{g Cu/L}$) on Shasta-strain rainbow trout (*Oncorhynchus mykiss*) exposed in soft water. Trout were sampled after 3, 7, 14, and 21 d of exposure to copper. The percentage of monocytes was consistently elevated at 26.9 $\mu\text{g Cu/L}$, and the percentage of lymphocytes was decreased. A consistent increase in the percentage of neutrophils occurred at 26.9 and 6.4 $\mu\text{g Cu/L}$. Respiratory burst activity was decreased for all concentrations at all sampling days, but a significant reduction occurred only at 14 and 21 d of exposure to copper. B-like cell proliferation was decreased. In short, all this means that the immune system of fish was affected by Cu exposure. Woody) by exposure to the higher copper concentrations. Proliferation results, however, had high variability. T-like cell proliferation and phagocytosis were not altered. Hepatic copper concentration was consistently elevated in trout exposed to 26.9 $\mu\text{g Cu/L}$; no correlation was found between hepatic copper concentration and the Immune system responses investigated. Consistent alterations in immunological parameters suggest that these parameters could serve as indicators of chronic metal toxicity in natural systems.

Buhl, KJ and SJ Hamilton. 1991. Relative sensitivity of early life stages of arctic grayling, coho salmon, and rainbow trout to nine inorganics. *Ecotoxicology and Environmental Safety*. 2:184-197.

Abstract: The acute toxicity of nine inorganics associated with placer mining sediments to early life stages of Arctic grayling (*Thymallus arcticus*), coho salmon (*Oncorhynchus kisutch*), and rainbow trout (*O. mykiss*) was determined in soft water (hardness, 41 $\text{mg liter}^{-1} \text{CaCO}_3$) at 12°C. The relative toxicities of the inorganics varied by four orders of magnitude; from most toxic to least toxic, the rank order was cadmium,

silver, mercury, nickel, gold, arsenite, selenite, selenate, and hexavalent chromium. In general, juvenile life stages of the three species tested were more sensitive to these inorganics than the alevin life stage. Among juveniles, no single species was consistently more sensitive to the inorganics than another; among alevins, Arctic grayling were generally more sensitive than coho salmon and rainbow trout. Based on the results of the present study, estimated no-effect concentrations of arsenic and mercury, but not cadmium, chromium, gold, nickel, selenium, or silver, are close to their concentrations reported in streams with active placer mines in Alaska. Thus, arsenic (as arsenite(III)) and mercury may pose a hazard to Arctic grayling and coho salmon in Alaskan streams with active placer mines.

Saiki, MK, DT Castleberry, TW May, BA Martin, and FN Bullard. 1995. Copper, cadmium, and zinc concentrations in aquatic food-chains from the upper Sacramento River (California) and selected tributaries. Archives of Environmental Contamination and Toxicology. 29(4):484-491.

Abstract: Metals enter the Upper Sacramento River above Redding, California, primarily through Spring Creek, a tributary that receives acid-mine drainage from a US EPA Super-fund site known locally as Iron Mountain Mine. Waterweed (*Elodea canadensis*) and aquatic insects (midge larvae, Chironomidae; and mayfly nymphs, *Ephemeroptera*) from the Sacramento River downstream from Spring Creek contained much higher concentrations of copper (Cu), cadmium (Cd), and zinc (Zn) than did similar taxa from nearby reference tributaries not exposed to acid-mine drainage. Aquatic insects from the Sacramento River contained especially high maximum concentrations of Cu (200 mg/kg dry weight in midge larvae), Cd (23 mg/kg dry weight in mayfly nymphs), and Zn (1,700 mg/kg dry weight in mayfly nymphs). Although not always statistically significant, whole-body concentrations of Cu, Cd, and Zn in fishes (threespine stickleback, *Gasterosteus aculeatus*; Sacramento sucker, *Catostomus occidentalis*; Sacramento squawfish, *Ptychocheilus grandis*; and chinook salmon, *Oncorhynchus tshawytscha*) from the Sacramento River were generally higher than in fishes from the reference tributaries.

Baatrup, E. Structural and Functional-Effects of Heavy-Metals on the Nervous-System, Including Sense-Organs, of Fish. Comparative Biochemistry and Physiology C-Pharmacology Toxicology & Endocrinology. 1991; 100(1-2):253-257.

Abstract: Today, fish in the environment are inevitably exposed to chemical pollution. Although most hazardous substances are present at concentrations far below the lethal level, they may still cause serious damage to the life processes of these animals. Fish depend on an intact nervous system, including their sense organs, for mediating relevant behavior such as food search, predator recognition, communication and orientation. Unfortunately, the nervous system is most vulnerable and injuries to its elements may dramatically change the behavior and consequently the survival of fish.

Heavy metals are well known pollutants in the aquatic environment. Their interaction with relevant chemical stimuli may interfere with the communication between fish and environment. The affinity for a number of ligands and macromolecules makes heavy metals most potent neurotoxins. The present Mini-Review highlights some aspects of how trace concentrations of mercury, copper and lead affect the integrity of the fish nervous system; structurally, physiologically and biochemically.

Oregon study shows copper from brake pads affects salmon

CORVALLIS, Ore., Oregon State University issued the following news release:

Copper deposited on roads by the wearing of brake pads is transported in runoff to streams and rivers, where it may play a key role in increasing predation of threatened and endangered salmon throughout California and the Pacific Northwest. According to a study released this week in *Environmental Science and Technology*, levels of copper as low as 2 parts per billion have a direct impact on the sensory systems of juvenile coho salmon. The skin of juvenile salmon is equipped with a special kind of warning system, said Nat Scholz, a researcher at the Northwest Fisheries Science Center, a branch of the National Oceanic and Atmospheric Association (NOAA) Fisheries Service. When a salmon is attacked by a predator, a chemical cue is released from the skin that signals danger to nearby fish. These fish smell the predation cue and take behavioral measures to avoid being eaten.

Oregon State University researchers working with scientists from NOAA Fisheries, found that fish exposed to low, environmentally realistic levels of copper had an impaired sense of smell and were less responsive to the chemical alarm signal. At elevated concentrations of copper, these predator avoidance behaviors were largely abolished.

Copper naturally occurs in aquatic environments at trace amounts as a background element. However, fluctuations due to run-off from storm events can increase the level of copper in the water from close to zero to more than 60 parts per billion in some instances, said Jason Sandahl, who co-authored the study while working as an OSU doctoral research assistant at the NOAA research laboratory.

'There is a fine line between active copper uptake and copper toxicity,' said Sandahl. 'We see problems when copper is pulsed into the water, temporarily elevating the copper higher than the natural background level. The olfactory, or scent, neurons are not able to maintain the normal regulation of copper, and the neurons are either disrupted or killed.' Salmon are known to avoid environmental gradients of copper, such as those created by point-source discharges. However, copper in stormwater is a diffuse form of non-point source pollution, and it is unlikely that juvenile fish could reduce their exposure through avoidance behaviors, said the researchers.

As a result of automobile braking and exhaust, higher levels of copper contamination have been observed in streams close to roads and highways. Building materials and certain pesticide formulations are also important sources of copper in western landscapes, said Scholz.

Recent monitoring of northern California streams following storm events found dissolved copper levels averaging 15.8 parts per billion per liter of water. Salmon exposed to copper at concentrations well below this average showed significant impairment to both their sensory physiology and predator avoidance behavior, said Sandahl, whose work on the study was funded in part by a National Institute of Environmental Health Sciences grant to OSU. The work was also supported by NOAA's national Coastal Storms Program.

Since the duration of storm events that cause elevated levels of copper in streams can be relatively short, investigators exposed juvenile coho salmon to copper for only a few hours. In earlier studies they found the onset of copper neurotoxicity to salmon olfactory systems occurs within a matter of minutes. Loss of sensory function is likely reversible, but may take hours or days of the fish being in clean water, said the researchers. If copper exposures are high enough to cause the death of olfactory sensory neurons, it will take several weeks to months for the fish to regenerate new neurons and recover.

The levels of copper contaminant used in the study were at or below current federal regulatory guidelines for heavy metals, said Jeff Jenkins, an environmental toxicologist in OSU's College of Agricultural Sciences. 'It's just like they were poisoned,' said Jenkins. 'Of all the chemicals we have looked at, this effect was clearly happening at levels well below the current copper standards for water quality. It raises the question of whether the current standards are as protective as we thought.'

The current study is an example of how contaminants can disrupt the chemical ecology of aquatic organisms. In the case of salmon, a sublethal loss of sensory function may increase predation mortality in urbanizing watersheds. The influence of copper on predator-prey interactions is the focus of ongoing research, with the eventual aim of linking individual survival to the productivity of wild salmon populations, said Scholz.

Though the study was conducted on juvenile salmon, the results are applicable to fish species in urban watersheds worldwide, said the researchers. Dissolved copper has been shown to affect the olfactory systems of chinook salmon, rainbow trout, brown trout, fathead minnow, Colorado pikeminnow and tilapia.

Barry, KL, JA Grout, CD Levings, BH Nidle, and GE Piercy. 2000. Impacts of acid mine drainage on juvenile salmonids in an estuary near Britannia Beach in Howe Sound, British Columbia. Can. J. Fish. Aquat. Sci. 57: 2032–2043.

Abstract: The abandoned copper mine at Britannia Beach, British Columbia, has been releasing acid mine drainage (AMD) into Howe Sound for many years. To assess the impacts of AMD on juvenile salmonids in the Britannia Creek estuary, we compared fish abundance, distribution, and survival at contaminated sites near the creek with uncontaminated areas in Howe Sound. Water quality near Britannia Creek was poor, particularly in spring when dissolved Cu exceeded $1.0 \text{ mg}\cdot\text{L}^{-1}$ and pH was less than 6. Beach seine surveys conducted during April–August 1997 and March–May 1998 showed that chum salmon (*Oncorhynchus keta*) fry abundance was significantly lower near Britannia Creek mouth ($0\text{--}1.2\cdot 100 \text{ m}^{-2}$) than in reference areas ($11.5\text{--}31.4\cdot 100 \text{ m}^{-2}$). Laboratory bioassays confirmed that AMD from Britannia Mine was toxic to juvenile chinook (*Oncorhynchus tshawytscha*) and chum salmon (96-h $\text{LC}_{50} = 0.7\text{--}29.7\%$ in freshwater and $12.6\text{--}62.2\%$ in 10 ppt water). Chinook salmon smolts transplanted to surface cages near Britannia Creek experienced 100% mortality within 2 days. These results demonstrated that juvenile salmonids are vulnerable to AMD from Britannia Creek: their abundance peaks during spring when Cu concentrations are highest and toxicity is greatest in surface freshwater, which matches their preferred vertical distribution.

Eisler, R. COPPER HAZARDS TO FISH, WILDLIFE, AND INVERTEBRATES:
A SYNOPTIC REVIEW. U.S. Geological Survey, Laurel, MD 20708

Excerpt specific to fish:

Fishes Adverse sublethal effects of copper on behavior, growth, migration, and metabolism occur in representative species of fishes at nominal water concentrations between 4 and 10 µg/L. In sensitive species of teleosts, copper adversely affects reproduction and survival from 10-20 µg Cu/L (Hodson et al. 1979; Table 5). Copper exerts a wide range of physiological effects in fishes, including increased metallothionein synthesis in hepatocytes, altered blood chemistry, and histopathology of gills and skin (Iger et al. 1994). At environmentally realistic concentrations, free copper adversely affects resistance of fishes to bacterial diseases; disrupts migration (that is, fishes avoid copper-contaminated spawning grounds); alters locomotion through hyperactivity; impairs respiration; disrupts osmoregulation through inhibition of gill Na⁺-K⁺-activated ATPase; is associated with tissue structure and pathology of kidneys, liver, gills, and other hematopoietic tissues; impacts mechanoreceptors of lateral line canals; impairs functions of olfactory organs and brain; and is associated with changes in blood chemistry, enzyme activities, and corticosteroid metabolism (Hodson et al. 1979).

Copper-induced cellular changes or lesions occur in kidneys, lateral line, and livers of several species of marine fishes (Gardner and LaRoche 1973). Copper-induced mortality in teleosts is reduced in waters with high concentrations of organic sequestering agents and in genetically resistant species (Hodson et al. 1979). At pH values less than 4.9 (that is, at pH values associated with increased aluminum solubility and toxicity), copper may contribute to the demise of acid-sensitive fishes (Hickie et al. 1993). Copper affects plasma Na⁺ and gill phospholipid activity; these effects are modified by water temperature and hardness (Hansen et al. 1993). In red drum, copper toxicity is higher at comparatively elevated temperatures and reduced salinities (Peppard et al. 1991).

Copper is acutely toxic to freshwater teleosts in soft water at concentrations between 10 and 20 µg/L (NAS 1977). In rainbow trout, copper toxicity is markedly lower at high salinities (Wilson and Taylor 1993). Comparatively elevated temperatures and copper loadings in the medium cause locomotor disorientation of tested species (Kleerekoper 1973). Copper may affect reproductive success of fish through disruption of hatch coordination with food availability or through adverse effects on larval fishes (Ellenberger et al. 1994). Chronic exposure of representative species of teleosts to low concentrations (5 to 40 µg/L) of copper in water containing low concentrations of organic materials adversely affects survival, growth, and spawning; this range is 66 to 120 µg Cu/L when test waters contain enriched loadings of organic materials (Hodson et al. 1979). Larval and early juvenile stages of eight species of freshwater fishes are more sensitive to copper than embryos (McKim et al. 1978) or adults (Hodson et al. 1979). But larvae of topsmelt (*Atherinops affinis*) are increasingly sensitive to copper with increasing age. Topsmelt sensitivity is associated with increasing respiratory surface area and increasing cutaneous and branchial uptake of copper (McNulty et al. 1994). Sublethal exposure of fishes to copper suppresses resistance to viral and bacterial pathogens (Rougier et al. 1994) and, in the case of the air-breathing catfish (*Saccobranchus fossilis*), affects humoral and cell-mediated immunity, the skin, and respiratory surfaces (Khangarot and

Tripathi 1991). Rainbow trout exposed to 50 µg Cu/L for 24 h—a sublethal concentration—show degeneration of olfactory receptors that may cause difficulties in olfactory-mediated behaviors such as migration (Klima and Applehans 1990). The primary site of sublethal copper toxicity in rainbow trout is the ion transport system of the gills (Hansen et al. 1993). Dietary copper is more important than waterborne copper in reducing survival and growth of larvae of rainbow trout (Woodward et al. 1994). Simultaneous exposure of rainbow trout to dietary and waterborne copper results in significant copper assimilation. Diet is the main source of tissue copper; however, the contribution of waterborne copper to tissue burdens increases as water concentrations rise (Miller et al. 1993). Rate and extent of copper accumulations in fish tissues are extremely variable between species and are further modified by abiotic and biological variables. Copper accumulations in fish gills increase with increasing concentrations of free copper in solution, increasing dissolved organic carbon (DOC), and decreasing pH and alkalinity (Playle et al. 1993a, 1993b). Starved Mozambique tilapia accumulate significantly more copper from the medium in 96 h than did tilapia fed a diet containing 5.9 mg Cu/kg DW ration (Pelgrom et al. 1994). The bioconcentration factor for whole larvae of the fathead minnow was 290 after exposure for 30 h, but only 0.1 in muscle of bluegills after 660 h (USEPA 1980). Prior exposure of brown bullheads (*Ictalurus nebulosus*) to 83 sublethal copper concentrations for 20 days before exposure to lethal copper concentrations produces higher copper concentrations in tissues of dead bullheads than in those not previously exposed; however, the use of tissue residues is not an acceptable autopsy procedure for copper (Brungs et al. 1973). Rising copper concentrations in blood plasma of catfish (*Heteropneustes fossilis*) seem to reflect copper stress, although the catfish appear outwardly normal. Plasma copper concentrations of catfish increase from 290 µg Cu/L in controls at start to 380 µg Cu/L in survivors at 72 h (50% dead); a plasma copper concentration of 1,060 µg Cu/L at 6 h is associated with 50% mortality (Banerjee and Homechaudhuri 1990). In rainbow trout, copper is rapidly eliminated from plasma; the half-time persistence is 7 min for the short-lived component and 196 min for the long-lived component (Carbonell and Tarazona 1994). Attraction to waters containing low (11 to 17 µg/L) concentrations of copper occurs in several species of freshwater teleosts, including goldfish (*Carassius auratus*) and green sunfish (*Lepomis cyanellus*); however, other species, including white suckers (*Catostomus commersonii*), avoid these waters (Kleerekoper 1973). In avoidance/attraction tests, juvenile rainbow trout avoided waters containing 70 µg Cu/L but were significantly attracted to water containing 4,560 µg Cu/L; a similar pattern was observed in tadpoles of the American toad, *Bufo americanus* (Birge et al. 1993). Copper concentrations in the range of 18 to 28 µg/L interfere with bluegill growth and prey choice (Sandheinrich and Atchison 1989). Copper interferes with the ability of fish to respond positively to L-alanine, an important constituent of prey odors; concentrations as low as 1 µg Cu/L inhibit this attraction response in some species (Steele et al. 1990). Increased tolerance to copper was observed in fathead minnows after prolonged exposure to sublethal concentrations, but tolerance was not sustained on removal to clean water. Copper tolerance in fathead minnows is attributed to increased production of metallothioneins (Benson and Birge 1985). Copper tolerance in rainbow trout seems dependent on changes in sodium transport and permeability (Lauren and McDonald 1987a).

Further Reading

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Foster, P., Hunt, D.T.E., and Morris, A.W. 1978. Metals in an acid mine stream and estuary. *Sci. Total Environ.* **9**: 75–86.

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