METALS: DETAILED CONCEPTUAL MODEL NARRATIVE

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Certain regions of the earth have naturally high concentrations of metals, and land disturbance in these areas can increase erosion and mobilize these metals into surface waters; human activities also can redistribute and concentrate metals in areas that are not naturally metals-enriched. When these metals are released into air, water, and soil, they can reach surface waters, and ultimately contribute to biological impairment of aquatic communities if they are biologically available at toxic concentrations. The following conceptual model describes the pathways by which point and non-point sources may contribute metals to surface waters, how water chemistry influences bioavailability, and how biologically available metals may impair aquatic life.

Model Format

The metals conceptual model diagram depicts sources and land use and channel alterations that contribute metals to surface waters near the top of the figure, leading down the diagram to steps in the causal pathway, proximate stressors (i.e., different forms of metals), modes of action, and eventually biological responses at the bottom. Key water chemistry conditions influencing metal forms also are shown. This narrative generally follows the diagram from top to bottom, left to right. For more information on interpreting CADDIS conceptual model diagrams, see the Conceptual Model Library homepage.

Linking Sources to Proximate Stressors

Metals enter surface waters by means of point and non-point sources (in tan octagons). A point source is a direct release to water from a discrete source, usually an outfall discharging effluent to surface water. Non-point sources include atmospheric emissions and land uses which contaminate soil with metals. Naturally metals-enriched regions such as the Colorado Mineral Belt become non-point sources when land cover alterations (e.g., devegetation due to agricultural or mining practices) expose rock and soil, which erode into surface waters. These pathways also apply to areas with legacy contamination, such as soil contamination from arsenical pesticide residues or long term industrial or urban land use. Reduced water transpiration due to devegetation and reduced infiltration due to the increased impervious surface cover (compacted soil, roofs, parking lots, and roads) increases the volume and velocity of stormwater runoff entering surface waters. Accelerated flow can incise channels, reducing bank stability and increasing bank and channel erosion. Bank and channel erosion also may be increased by livestock grazing and trampling. Stormwater turbulence or intentional dredging can re-suspend sediments, which may allow sediment-associated metals to partition into the water column, or transport contaminated sediment into previously uncontaminated areas.

Metals entering the atmosphere from tailpipe and stack emissions are precipitated onto land or directly onto water. Episodic, pulsed exposures occur when metals precipitated onto land are washed into surface waters during storms. Smaller runoff events may result from activities such as washing cars or watering lawns and landscaping. The severity of episodic exposures is related to the amount of dry deposition built up in the period between events, saturation levels of non-impervious areas, and the volume of water discharged. The highest levels occur early in the runoff period, or in the "first flush". Metal mobility can be increased by acid rain or soils with acid-forming parent material, fertilizers, tailings or other amendments. More gradual releases occur over periods of snowmelt which can contribute metals to both soil moisture and direct runoff. More detailed information on metals sources and factors conveying metals to surface waters can be found in Marsalek et al. (2006).

Waste from residential and commercial areas may be directed to septic systems, landfills or wastewater treatment plants. Septic systems and landfills can contribute to metals contamination via leachate entering subsurface waters (e.g., groundwater) and eventually surface waters. Wastewater treatment plants, on the other hand, discharge metals-contaminated effluent directly into surface waters. Industrial activities contributing metals to the environment include the storage, refinement, and combustion of fossil fuels and the manufacture of a variety of goods. Waste from industrial facilities may be treated on-site and discharged, stored on-site, or directed to off-site landfills or wastewater treatment plants. Leachate and surface runoff from on-site or off-site storage and disposal areas may transport metals to surface waters. Mining also may involve on-site storage and disposal of wastes, which may contribute metals to surface waters via similar pathways.

Linking Proximate Stressors to Biological Impairment

Once in water, the bioavailability and toxicity of a metal is determined by its partitioning and speciation, which are determined by several environmental parameters (e.g., pH, temperature, redox potential, ionic strength, presence of methylating microbes, and the availability of binding sites). Based on these parameters, free metal ions may precipitate, form complexes with ligands (i.e., biotic or abiotic binding sites), become transformed to organometallic compounds (e.g., methylation in mercury), or sorb to solid particles. For more details on metals speciation, see Langmuir et al. (2004).

The metal species of primary toxicological concern are free ions. For many metals, acute toxicity results from binding of free metal ions to chloride cells of the gill epithelium, disrupting osmoregulation and leading to mortality (DiToro et al. 2001). Certain metal forms may diffuse into the gill epithelium, but these absorption routes are considered minor relative to free ion binding. Toxicity associated with dietary bioaccumulation of metals and, for some metals, biomagnification within food webs can occur when there are sustained exposures in habitats with persistent contamination; in addition, food source and feeding mode are key factors determining whether dietary bioaccumulation occurs. Acid mine drainage can present a physical cause of impairment when drainage water mixes with the higher pH water of a receiving stream and metal hydroxides precipitate. The flocculate that results can coat the streambed and smother benthic habitats and organisms.

Interactions with gill membranes can damage tissue and impair the ionoregulatory processes of chloride cells. Once within the organism, metal toxicity may occur by the substitution of nutrients with toxic analogs (e.g., Pb ↔ Ca), improper insertion into enzyme active sites (e.g., Se ↔ S), oxidative injury via free radical cycling, and nonspecific binding to nucleic acids and proteins. Analog substitution and nonspecific binding impair proper function of biomolecules, which in turn influences the physiological health of the organism. Impairment of proteins associated with organelle and cellular membranes affect membrane integrity, leading to breaches and impaired function. At the gill, impairment of chloride cells on the gill affects ion regulation. Internally, impairment of mitochondrial membranes cause leakage of oxyradicals generated via the electron transport pathway. Oxyradicals in turn can cause oxidative damage leading possibly to cell death.

The physiological mechanisms of metal toxicity may translate into a broad spectrum of organism-level effects, ranging from altered behavior (avoidance of contaminated areas, increased susceptibility to predation or reduced success of predators) to outright lethality. Responses detectable in biosurveys often are limited to increases in the relative abundance of metal-tolerant species, decreases in metal-sensitive species, and certain physical anomalies observed in fish (e.g., selenium-associated spinal deformities, blackened tails due to collapse of chromophores, excess mucous production due to gill irritation, and impaired ionoregulation). Examples of species often considered metal-tolerant include chironomids, caddisflies, small-bodied stoneflies, yellow perch and central stonerollers; examples of metal-sensitive species include bivalves, mayflies, and salmonids. However, it should be kept in mind that biotic responses are both taxa- and metal-specific. For more details on the ecological effects of metals, see Kapustka et al. (2004).

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