Emerging Contaminant Issues from an Ecological Perspective

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ABSTRACT

An ultimate goal of toxic substance hydrology is to understand the ecological, biological and human health implications of the toxic substances released by human activities. It is known that contaminants can be toxic, but it can be difficult to unambiguously identify their effects in specific circumstances. Thus controversy and contentious debate can occur when contaminants are suspected of causing ecological damage. Our knowledge of how contaminants exert their effects on ecosystems has advanced in important ways in recent years, and will change even more rapidly in the years ahead. These changes have the potential to reduce some of the ambiguities in evaluations of the implications of contamination. The new knowledge could create a demand for changes in the basic approaches for contaminant management and changes in the tools employed in those approaches. Changing approaches and tools will be a challenge for existing institutions, including regulatory agencies and the USGS. This paper attempts to summarize some of the broad "emerging contaminant issues" that could result in improved management approaches. These issues are relevant to both the newly discovered potential agents for ecological damage (Thurman, 1999) and some of the traditional contaminants.

INTRODUCTION

Managing the contamination problems of the future will require a strong partnership between experimental scientists, field scientists and managers. Never has there been a greater need for application of sophisticated contaminant-relevant principles from geochemistry, biology, ecology and hydrology. There are several reasons for this:

1. Many of the instances where it is easiest to identify the ecological effects of chemical contamination have been at least partly resolved by traditional management approaches. Waste treatment improved after passage of the Clean Water Act in 1970, and some chemicals were banned because of obvious adverse ecological effects (organochlorine pesticides, polychlorinated biphenols (PCBs), and tributyl tin). Some inputs of severe industrial pollution were eliminated as heavy industries moved away from North America. Overt instances of chemical effects (fish kills, instances where fauna were completely eliminated by toxins) are now less common than they once were. Complete elimination of fauna around outfalls is rare. Populations of large piscivorous birds are recovering after the ban of organochlorine pesticides and PCBs.

2. Discoveries in animal populations of chemically induced problems such as endocrine disruption (Colburn and Clement, 1992), teratogenicity (Skorupa and others, 1998), and chemical interference with reproduction at very low level exposures (Hook and Fisher, 1998) illustrate that at least some contaminant effects are manifested in ways not detected by traditional approaches. The reduced frequency of obvious contaminant effects does not mean that contaminants no longer have significant influences on ecosystems. It is more likely that the remaining effects are manifested in ways that are difficult to detect with traditional tools. Therefore,

toxicological mechanisms may not yet be appreciated or even recognized for some types of modern chemical contamination problems.

3. Even where chemical concentrations of contaminants are relatively high by most standards (abandoned mine lands; selenium and methyl-mercury contamination in some specific instances), controversy exists about ecological implications.

MANAGEMENT UNCERTAINTIES

Uncertainties about the ecological implications of contamination are an important detriment to effective environmental management. Costs of management, mitigation or remediation of contamination will grow as the most overt problems are resolved and the more widespread or complex problems are addressed. Optimal solutions to contamination problems can be facilitated by better understanding ecological implications. For example, in restoring damage to rivers from mining operations, is it necessary to completely remove all contaminated floodplain soils, or is it adequate to stabilize banks and let some contamination remain in the stream? Unambiguous knowledge of the metal concentrations and toxicant pathways that affect the status of fish resources in the river could greatly aid such decisions. Perhaps most importantly, we may be quickly approaching a state where intuitive management of environmental problems generates unacceptable risks. If a proposed solution to an environmental problem is single-minded, it may create problems just as bad or worse than the one being resolved. For example, methyl tert-butyl ether (MTBE) was prescribed as an additive to oxygenate gasoline and thereby reduce air pollution. However, its solubility created an unanticipated water pollution problem that we are only beginning to quantify. Furthermore, restoring marshlands or attaining zero net loss of wetlands by trading development of one marsh for restoration of another may be ostensibly desireable for reducing or reversing effects of past mistakes in land use. But biological availability of mercury through methylation processes is enhanced by the area of wetland in a watershed, and mercury contamination of soils and sediments may be widespread because of atmospheric inputs (Wiener, 1999). What are the tradeoffs (for example, in San Francisco Bay) when wetland restoration projects could make mercury contamination of fish and piscivorous birds increasingly problematic?

Today's water-quality criteria served an important legal purpose, and have been effective in reducing some forms of environmental pollution. But their ambiguities in terms of scientific accuracy have become a serious limitation to future applications. Management of contaminants in natural waters is presently accomplished by directly comparing the concentration of contaminant in water or sediment with a concentration predicted to cause adverse ecological effects. Most recent advances in regulatory science have emphasized improving the geochemical basis for incorporating environmental pollutant concentrations into water quality guidelines (DiToro and others, 1990). The new geochemical approaches include the switch from total metals in water to dissolved metals; incorporation of site-specific "water effects ratios" to correct for metal speciation; and use of equilibrium partitioning theory to predict pore water concentrations of some non-ionic organic compounds. They also include proposals to employ comparison of extractable metal and acid volatile sulfides (AVS-SEM) in sediments to model biologically available metal from pore waters.

Even if the geochemical approach is highly accurate, the environmental concentration must be compared to toxicity predicted by traditional toxicity testing methodologies. When dissolved concentrations of metals in nature, for example, are compared to the toxicities predicted by traditional bioassays environmental concentrations are well below LC50 values. Does this mean that there are no adverse effects from contaminants remaining in nature? Or is the toxicity value in these comparisons somehow under-estimating the contaminant concentrations that induce ecological implications? Suggestions of the latter lie in a growing new body of biological knowledge of contaminant effects.

The basic paradigm for toxicity testing was developed in the 1970's and remains unchanged. Recently, however, new knowledge and new tools provide alternatives to a number of the long-recognized uncertainties about the ecological implications of contaminants. These are best understood via comparison with traditional approaches.

Exposure Pathways: All existing bioassay methodologies (including sediment bioassays) predict toxic concentrations of contaminants from a dose delivered only via the dissolved route. It is known that animals inhabiting a contaminated environment ingest contaminated food. It is known that contaminant uptake from food by aquatic animals can occur. The contribution of the dietary pathway to dose and toxicity has remained controversial, however, at least partly because we could not quantitatively state how much contaminant was taken up from food. New protocols and models now clearly show that dietary exposure to contaminants is quantitatively important for some contaminants (although it may vary somewhat with contaminant and circumstance) (Luoma, 1996; Thomann and others, 1995; Wang and others, 1996). It is also clear that dietary exposure and dissolved exposures are additive. Therefore experiments employing dissolved exposures alone underestimate the dose an animal receives in nature from a combination of dissolved and diet exposures. Combined with the abbreviated exposures (24 – 96 hours) typical of most toxicity tests, these limitations result in underestimations of contaminant concentrations that cause adverse effects in nature (as much as 100 fold for Se; Luoma, 1996).

New toxicity testing protocols that include exposures to contaminated diet show surprising results. Trout fed food from a metal contaminated river show adverse effects not observed in simple dissolved replications of the concentrations found in the contaminated system (Woodward and others, 1995). Although an excess of sulfide over metal in a sediment may reduce pore water metal concentrations, dietary uptake of sulfide-bound metals has been demonstrated (B. G. Lee, USGS, written communication). Therefore dietary uptake of metal and toxicity can result in sediments predicted to be innocuous based upon metal-sulfide differences (B. G. Lee, USGS, written communication). Exposure of zooplankton to dissolved Ag concentrations in the range that occurs in contaminated natural waters (0.001 - 0.100 µg/L) has no effect on the animals. Hook and Fisher (1998) exposed phytoplankton to those silver concentrations then fed the phytoplankton to zooplankton. Both egg production by females and egg hatching in the zooplankton were affected by silver concentrations as low as 0.05 µg/L. Multiple pathway bioassays are more complicated to employ than the traditional dissolved exposures, so it will be challenging to incorporate such tests into management-related protocols. Until multi-pathway tests are refined, field scientists should be aware that at least some species are more sensitive than predicted from toxicities based upon dissolved exposures alone.

Effects on reproduction: The recent debate about effects of endocrine disruption illustrate the extreme sensitivity of reproductive processes in animals to chemical disruption. Mechanisms for disruption of reproduction include hormone disruption (pharmaceuticals; organochlorines), other modes of chemical interference with gamete production or embryo development (disruption of tertiary protein structure by Se substitution for sulfur) or even by disruption of energetics. Recruitment is as important as mortality for a population; so the relevance of reproductive toxicity cannot be disputed. Nevertheless, testing approaches are not routinely available to evaluate reproductive disruption; although such tests could be relevant for both "emerging contaminants" (Thurman, 1999) and many traditional contaminants (e.g. cadmium, silver, methyl mercury, selenium, PAHs, modern pesticides). The traditional toxicity tests employ toxicity to adult animals. These results are then corrected by a value derived from what are termed "chronic" exposures. Chronic tests usually consider a single life stage in isolation and can be abbreviated compared to the generation time of the life stage. Life cycle tests or specific tests of reproductive function are necessary to evaluate chemical interference with reproduction. These experiments are more difficult than traditional toxicity tests. Long term studies supported by the USGS Toxic Substances Hydrology program have shown, however, that reproductive status is more feasible to evaluate in the field than is toxicity. A demand for field evaluations might arise as awareness of reproductive sensitivities increases. It is not unreasonable to incorporate this type of effect into water quality evaluations of monitoring and field data (M. H. Hornberger and others, USGS, written communication). A combination of dietary exposure evaluations, focus on reproductive disruption, and field studies that evaluate reproductive activity and effects on fecundity, offer immediate possibilities for expanding the sophistication of knowledge about important contaminant effects.

Species-specific responses: Traditional bioassays evaluate toxicity for relatively few organisms. It is assumed that the response of these surrogate species can be extrapolated to the plethora of species that occupy communities in nature. Aside from the obvious limitations to choosing "the most sensitive species" for bioassays (Cairns, 1986), this approach is not consistent with how contaminants exert their effects in nature. Defaunation of ecosystems is not the mode of action of modern contamination. Contamination first eliminates the most sensitive species at a site. And as contamination increases, progressively less sensitive species are eliminated. We know little about which species are the most sensitive to contamination (and thus most likely to be eliminated). Only a few authors have directly evaluated sensitivities in toxicity tests (Clements, 1991). Where these studies have been done they have linked laboratory outcomes with field expectations in unprecedented ways. For example, it is recognized that some species of mayflies are among the first to disappear from metal contaminated streams. Paucity of mayflies (or mayfly species) are, therefore, a relatively sensitive indication that metals are an important variable structuring stream communities. Such knowledge offers the ecologist a basis for developing hypotheses to separate metal effects from other influences on community structure. Mechanistic studies may be another powerful way to compare sensitivities among species. New mechanstic approaches to studying bioaccumulation allow unambiguous comparisons of exposure differences among species. Bioaccumulation models, conceptual understanding of detoxification and mechanistic understanding of the most sensitive aspects of toxicology together will aid species-specific and, thus, site-specific evaluation of toxicity from monitoring data in the years ahead. The implicit, practical and traditional view that toxicity is biologically generic will yield in the future to the view that species-specific attributes determine susceptibility to contaminants.

Unambiguous linkage of field and experiment or mechanistic study: The traditional approaches to regulatory science lack unambiguous protocols for linking field observations with laboratory evaluations of toxicity. New protocols and bioaccumulation models might allow some solutions to this problem. Bioaccumulation is a direct indicator of the dose of a bioaccumulative chemical experienced by an organism. As described above, bioaccumulation can be modeled from field geochemical concentrations and species-specific physiological information (Luoma, 1996). Bioaccumulation can also be monitored in the field; tissue concentrations of bioaccumulative chemicals can thereby be used for model verification. Translating multi-media geochemical data into exposure or bioaccumulation information via multi-pathway bioaccumulation models is increasingly feasible. In their simplist applications such models might evaluate potential resource contamination under different conditions (for example methyl mercury or persistent chemical contamination of the flesh of edible species). Modeled bioaccumulation might replace the search for correlative agreement between water, sediment and tissue concentrations of contaminants and thus link hydrologic and geochemical monitoring to bioavailability and ecosystem effects .

Modeled or observed tissue concentrations of contaminants must ultimately be related to adverse effects on biota or communities to be maximally useful. A small body of work suggests that it will be possible to relate critical tissue residues of a contaminant (or some fraction of the tissue residue) to a decline in physiological health within an organism itself (Luoma, 1996). It might also be possible to use residues in an indicator species to link observed pollutant concentrations with the expected disappearance of specific groups of species

The value of hydrologic and geochemical monitoring will expand as sophisticated biological interpretations are increasingly feasible.

SUMMARY

Although we are beginning to appreciate the complexities of contaminant effects in nature, important uncertainties remain. It is known that contaminant exposures in nature are complex but exposures are adequately studied only in rare circumstances. It is known that species differ widely in their vulnerability to contaminant effects but the role of basic biology in contaminant vulnerability is not adequately known. Generalizations about the groups of species most vulnerable to a specific type of contamination are rare. It is clear that contamination can simplify communities and affect population processes, but that knowledge is not yet sufficient to extrapolate over a variety of sites. As a result, consensus does not exist about the implications of changes in ecologically fundamental factors such as community composition. Long-term, interdisciplinary study of contaminated sites, a cornerstone of the Toxic Substances Hydrology Program of WRD/USGS, has been a key approach to providing some of the new advances in understanding contaminant implications. A great advantage of the long-term approach in field studies is that the hydrologic, geochemical and biological complexities that typify nature can be progressively resolved over critical temporal frequencies. Understanding the role of contaminants relative to other sources of stress requires such multi-disciplinary resolution. It will be critical in the future that laboratory studies that facilitate model development, and knowledge of sensitivities at different levels of biological organization be coordinated with persistent field studies characteristic of the Toxic Substances Hydrology Program.

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