Managing Multimedia Pollution for a Multimedia World

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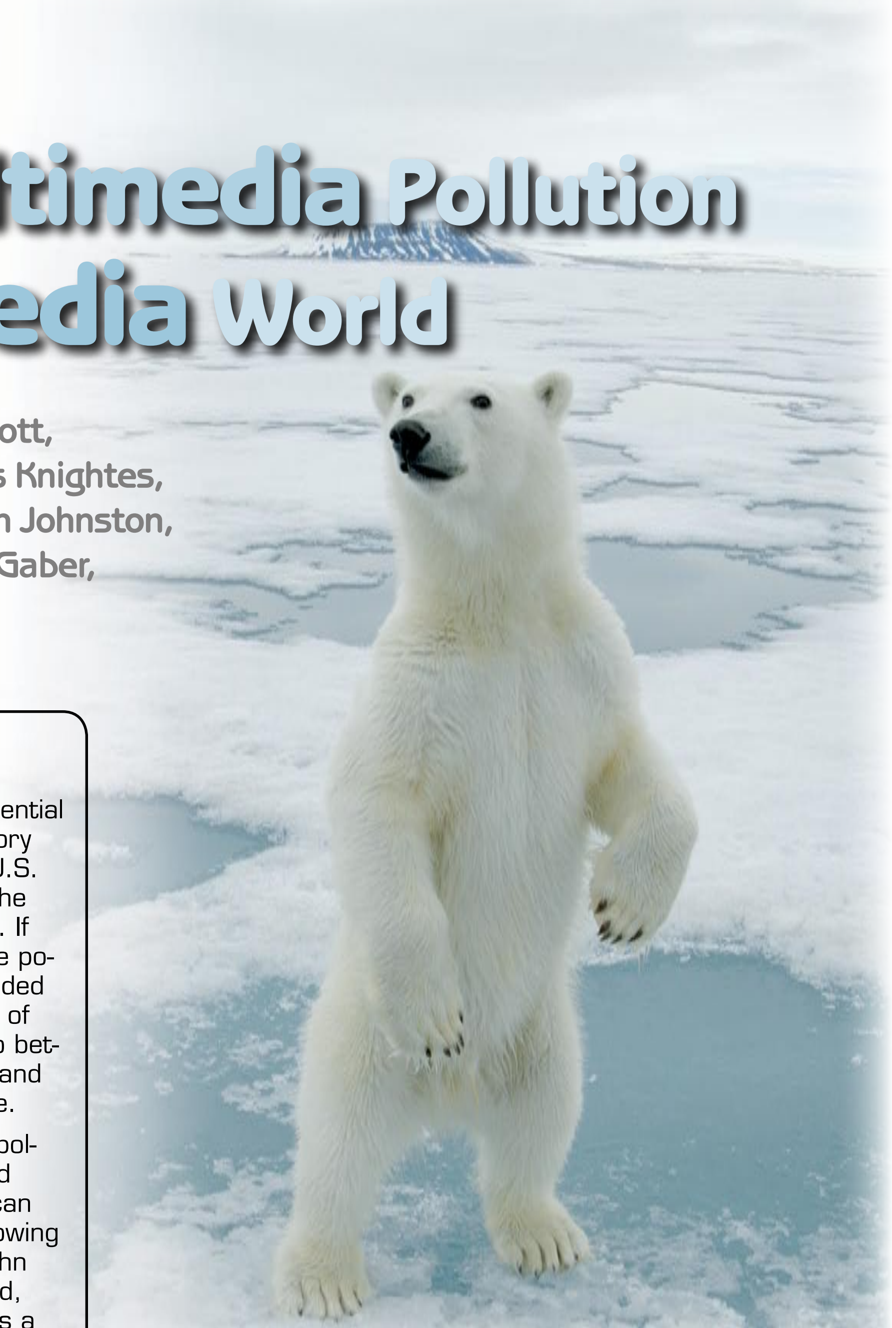

NO POLLUTION IS AN ISLAND

Due to climate-change-induced melting of essential sea ice habitat and a lack of effective regulatory mechanisms to mitigate further losses, the U.S. Fish and Wildlife Service is now considering the polar bear for listing as a threatened species. If we could place ourselves for a moment in one potential future of the polar bear, similarly stranded in the Arctic Ocean on the last tenuous piece of ice called *Ephemeral Hope*, we might begin to better appreciate how important understanding and actively managing multimedia pollution may be.

To expose the inherent nature of multimedia pollution, and how we are beginning to see it and deal with it as environmental managers, we can also consider the underlying truths in the following re-stating of the great Renaissance writer John Donne's work: "No man's emission is an island, entire of itself; every man's emission becomes a piece of the continent, a part of the sky, a parcel of the ocean, where any man's pollution diminishes me, because I am involved in pollution; and therefore never send to know for whom that plume tolls; it tolls for thee."

How "complex" and "multimedia" is the environmental management world becoming? As one measure, the U.S. Environmental Protection Agency (EPA), a historically single-medium management paradigm, has been rapidly expanding collaborative research over the past 10 years, both among its single medium-based program offices and across key environmental management arms of the federal sector.

The ubiquitous presence of excess greenhouse gases, nitrogen, sulfur, mercury, and other persistent, bioaccumulative, and toxic pollutants is the writing on the wall that we must unhesitatingly find ways to better understand and manage the multimedia world in which we live.

Through modest attention to the information highway we ride upon each day, we are increasingly aware of the intent, actions, and reactions of local, state, and federal governments, regional compacts, and international organizations to protect the quality of the water we drink, the air we breathe, and the food we (and our pets) eat. Just as with the globalization of our economy, these scales of government interact in many ways, each from its own vantage point, to optimally manage or otherwise influence critical aspects of our multimedia world. As one example, we are currently witnessing a proliferation of resolutions and actions affirming county government support for addressing climate change. On the other end of the spectrum, most citizens are familiar with the successes of the international effort to control chlorofluorocarbons (CFCs) under the Montreal Protocol on Substances that Deplete the Ozone Layer of 1987. Exemplifying an inherently adaptive science-based approach, the treaty has been amended five times to reflect an updated base of knowledge and data on causes and effects of ozone depletion.

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If we are going to be successful in improving upon the use and sustainability of the Earth's resources for future generations, we must increase cooperation with one another at the political, scientific, and technological interfaces of our existing institutions. The operative words are multimedia, integration, and adaptation. This article considers several aspects of how this is already taking place to deal with compelling, contemporary environmental management issues. In addition to highlighting multimedia-modeling approaches undertaken to address a range of carbon-based chemicals (i.e., persistent organic pollutants, or POPs), this article also provides reflections from the five articles that follow in this issue of *EM*. The articles offer, among other concepts, key insights into multimedia modeling and decision-making, focused on sulfur, nitrogen, and mercury pollution. In introducing these discussions, we first provide some useful background and perspective to underscore the cascading issues of science, technology, and modeling that underlie the demands placed upon today's environmental managers.

A MULTIPLICITY OF ASSESSMENT DIMENSIONS

In spite of elevated participation for today's citizens and environmental managers, the underlying complexity of achieving environmental protection, and explaining it, is getting harder. The sheer amount of information and the integrated reasoning required for environmental decision-making is progressively extending beyond initial intuition and quick summary. The increased complexity faced by today's environmental managers, scientists, engineers, and technologists reflects a multitude of interwoven body-politics that cross a multiplicity of technical concerns (see Figure 1). The principal assessment dimensions of today's most pressing environmental problems include scoping of multiple media (e.g., air, soil, water); multiple stressors (e.g., nitrogen, mercury, climate change); multiple pathways (e.g., inhalation and ingestion); multiple receptors (e.g., humans and animals); multiple spatial and temporal scales (e.g., site-specific, regional, national, global); and multiple endpoints (e.g., hazard and cancer risk to receptors, valuations of economic benefits from eco-tourism and fisheries).

Modern technical problem solving is more than just the "multimedia" dimension. In the context of supportive modeling efforts and the parlance of today's terminology,

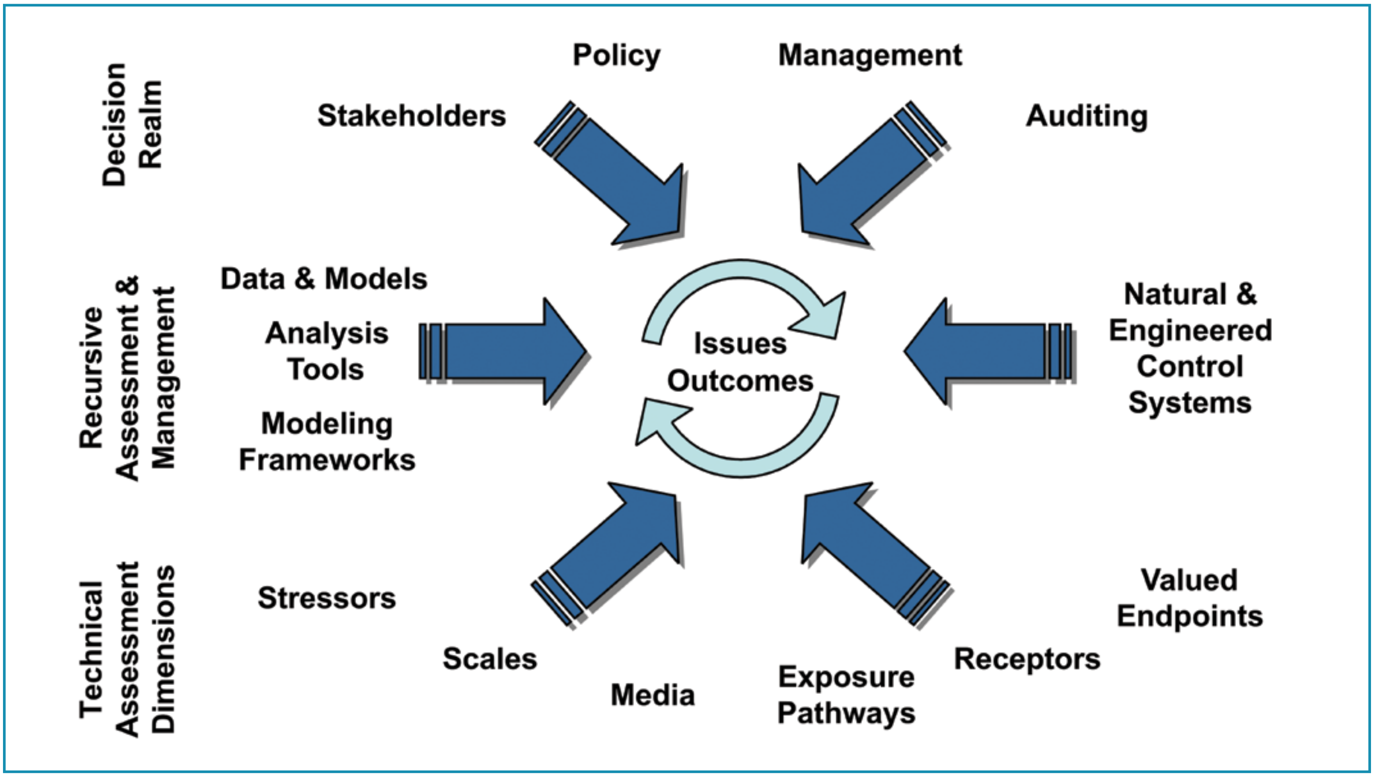

Figure 1. Multidisciplinary integrated decision-making framework for adaptive management of modified environmental systems.

we often associate this term with a broader reality of what is increasingly referred to as "integrated" assessment modeling. Such assessments may encompass two or more areas of technical concern, where a multimedia approach is often included in some form or another. Integrated modeling is an integral aspect today in interfacing decision-makers with issues, actions, and outcomes. Aspects of the underlying evolution of modeling capabilities have focused on development of better science, as models and data, and more facilitative modeling system infrastructures. The latter represents an ongoing refinement and expression of technology-based "standards" for execution management of software components, data acquisition, input-output management schema, visualization, uncertainty analysis, and communication of assumptions and results to participants in the decision realm.

From Single-Medium to Multimedia Assessment and Management

In previous decades, environmental management focused heavily on the obvious contamination "hot spots." In retrospect, the problems of contaminated landfills, smog-filled cities, and threatened water supplies were, for the most part, easily managed. Even before industrialization, the great ages of agriculture had already led to the birth of civil engineering, which set about the first task environmental managers undertook—providing clean drinking water free from pathogens. In all of this, single-medium investigations and associated modeling approaches served well as the workhorses of progress in these efforts, having extracted great benefits for society from an often limited understanding of how the world actually worked. Conversely, today's problems often require a systems approach, and increasingly employ some form of integrated modeling. For example, calculations for determining the Total Maximum Daily Loads (TMDLs) for a pollutant in a waterbody have moved from point-source analysis to nonpoint sources, extending further to atmospheric inputs where appropriate. Hazardous waste risk assessment has moved from analysis of leaching to groundwater and associated impairment of drinking water wells to complex analyses of multimedia releases of contaminants from numerous source types, evaluating both human and ecosystem receptors. Similarly, EPA's Office of Air and Radiation's toxics release impacts analysis now considers the full breadth of indirect pathways and impacts.

POPS—ORGANIC TRANSBOUNDARY TRAVELERS

Predominantly arising from manufacturing production in the latter half of the 20th century, persistent organic pollutants (POPs) include industrial chemicals like polychlorinated biphenyls (PCBs) and the pesticide DDT that (a) do not break down easily in the environment, (b) tend to bioaccumulate as they move up the food chain, (c) may be harmful to people and wildlife, and (d) have the propensity for long-range transport. Between 1998 and 2001, the United States signed two international treaties and one executive agreement to reduce production and use and regulate trade and disposal of certain POPs and other chemicals. The agreements—the Stockholm Convention on Persistent Organic Pollutants (POPs), the Rotterdam Convention on Prior Informed Consent, and the POPs Protocol to the Aarhus Convention on Long-Range Transboundary Air Pollution[1]—represent an example of attempts to establish key cooperation between the United States and other nations to mitigate the effects of an important class of carbon-based chemicals, those that travel great distances.

The Stockholm Convention on POPs was ratified by the requisite 50 parties needed to make it binding international law for those governments on May 17, 2004. For the most part, the "dirty dozen" POPs (see sidebar opposite) slated for initial phase-out were already strictly regulated in U.S. commerce. To ratify the treaties in the United States, Congress will need to amend two federal laws: the Toxic Substances Control Act, governing industrial uses of chemicals, and the Federal Insecticide, Fungicide, and Rodenticide Act, which regulates pesticide sale and use.[1] A central aspect of current debate in reaching consensus in the United States is the provision of the "living" Stockholm agreement that allows for additional listing of new POPs, which, by treaty, can be promulgated through international committee. An example POP proposed by several environmental organizations for listing is perfluorooctanoic acid and its salts (PFOA), which have a ubiquitous presence in the production processes of a broad range of U.S. manufacturing sectors (e.g., Teflon).[2]

Multimedia Modeling of POPs

Tracing the movement of most POPs in the environment is complex because these compounds can exist in different phases (e.g., as a gas or attached to airborne particles) and can be exchanged among environmental media. Some POPs can be carried for many miles when they evaporate from water or land surfaces into the air, or when they adsorb to airborne particles. POPs may return to the landscape via wet or dry deposition, and subsequently travel through oceans, rivers, lakes, and biota. Since POPs can travel thousands of miles, the use of legacy POPs in other countries will likely result in increased exposures to humans and ecosystems throughout North America. Although the United States and Canada have greatly curtailed the use of the "dirty dozen" POPs, there is evidence that additional POPs are currently in significant use, and will likely need to be further regulated. For example, a new class of POPs representing a third of organic chemicals in commercial use today has been described that do not bioaccumulate in fish, but which do accumulate in air-breathing animals due to a high octanol-air coefficient (e.g., endosulfan).[3]

To this end, there has been widespread interest in multimedia modeling of POP transport at large scales. Examples include the work of Arnot and Gobas, who define a food web model for tracking the bioaccumulation of POPs in an aquatic ecosystem;[4] Scheringer and Wania, who summarize two approaches for the multimedia modeling of POP fate and transport on a global scale;[5] McKone and MacLeod, who provide a review of the multimedia mass-balance approach to POP fate, transport, and exposure modeling

The "Dirty Dozen" POPs

1. PCBs
2. Dioxins
3. Furans
4. Aldrin
5. Dieldrin
6. DDT
7. Endrin
8. Chlordane
9. Hexa Chlorobenzene (HCB)
10. Mirex
11. Toxaphene
12. Heptachlor

over large (i.e., regional, continental, and global) scales;[6] and Mackay and MacLeod, who discuss the importance of multimedia environmental modeling in assessing fate and transport of POPs and other bioaccumulative intermedia contaminants.[7] Mackay and MacLeod also advocate incremental model development (i.e., slowly adding to model complexity) and view the fugacity approach (i.e., equilibrium-based mass transfer across compartments) as

> **What we do to minimize pollutant mass in one medium may increase it in another.**

a practical method of simplification, while Hertwich et al. performed uncertainty analysis on the CalTOX multimedia fate and exposure model, as applied to selected POPs,[8] and found that making steady-state assumptions with regard to atmospheric processes can lead to underestimation of exposure. These examples point to the complexity of the problem statement, and the key role of integrated modeling in its solution.

INTEGRATED MULTIMEDIA MODELING GALLERY

It is important to note that what we do to minimize pollutant mass in one medium may increase it in another. By overestimating the release of pesticides in run-off, for example, we may unknowingly underestimate the impacts of ingestion or inhalation to terrestrial species. In securing a sustainable environment, the idea of worst-case single-medium modeling, even within a multimedia-modeling construct, is no longer a simple contract between modeler and decision-maker. Associated decisions are, for one, increasingly less affordable. It may also render a decision process subject to undermining via the Data Quality Act of 2001. A common goal of modern assessments and decision-making is, thus, the ability to optimally manage, with our best science (as models and data), the relative uncertainties associated with simultaneously allocating pollutant mass across all media-pathway combinations.

Atmospheric Deposition of Nitrogen and Sulfur

Acids precipitate from our skies when oxidized emissions of sulfur (SO_2) and nitrogen (NO_x) react in the atmosphere to form nitric and sulfuric acid. Once formed, these compounds, along with various metal and organic compounds, are eventually deposited to both water and land in either a wet form (i.e., rain, snow, or fog) or a dry form (i.e., gases and particles). Atmospheric deposition of "basic" ammonia (NH_3) emissions is also implicated in the biologically mediated acidification of soil systems. Higher stacks and particle capture systems erected to initially protect local communities from industrial air emissions have consequently, by design, enhanced the long-range transport of SO_2, NO_x, and NH_3. Resulting in a major regional-scale pollution problem, these pollutants now travel hundreds of miles, often crossing state and national borders. Excess sulfur and nitrogen deposition leads to acidification and eutrophication of lakes and streams, reduced aquatic species diversity and abundance, elevated ozone concentrations in the lower atmosphere, increased fish mercury levels, and trophic status alteration of downstream coastal estuaries.

On page 12, Dennis et al. summarize our current understanding and approaches to modeling the atmospheric deposition of SO_2, NO_x, and NH_3. The potential significance of the "acid rain" problem was first identified some 40 years ago, with major regulatory approaches engaged through the Clean Air Act Amendments of 1990. Expressing the recursive nature of adaptive management, acid rain is receiving increased multimedia attention of late on the East Coast, as we have realized the need to more adequately protect ecosystem health. The Clean Air Interstate Rule is a product of multimedia modeling, a prime example of how it is being used today to support national decision-making. Detailed by Dennis et al., a growing focus is also placed on the problematic deposition of nitrogen in western U.S. states. Both regional problems are affecting terrestrial, freshwater, and coastal ecosystems across multiple spatial and temporal scales. The story is similar for other industrialized areas of the world. To better understand and predict deposition and behavior of sulfur and nitrogen, emphasis is being placed on linking airshed, watershed, and surface water models within a common decision framework. One of the great challenges is balancing the large regional scales and fine grids imposed by the fast nature of air transport.

Nitrogen Impacts to Estuaries and Coastal Waters

In addition to the acidification of freshwater systems, a critical multimedia problem is also found in the mitigation of nitrogen impacts to estuaries and coastal waters. Its solution will require tracking and, ultimately, control of the combined and relative ecosystem impacts from both air emissions and a wide array of other land-based releases. On page 19, Hameedi et al. discuss sources of reactive nitrogen in these systems. Sources can include fertilizer applications, discharge of municipal sewage and certain industrial effluents, leaking sewer systems, aquaculture operations, fossil-fuel combustion (e.g., power plants and automobiles), manure-laden runoff from coastal farms, atmospheric deposition of emissions from farms and fields (i.e., bi-directional exchange of NH_3), runoff from forests and pastures, and inflow from adjacent coastal waters. Spanning multiple media, the most significant sources of nitrogen to estuaries and coastal waters are often attributed to human sewage, agricultural operations, and atmospheric deposition.[9]

Pointing to the complexity in finding suitable management approaches, the dominance of a given source, fate and transport characteristics, and ecosystem response to various forms of reactive nitrogen are highly dependent upon locale and ecosystem structure. Unlike freshwater systems, there remains a lack of established concentration-based benchmarks for nitrogen in coastal waterways that one can use to predict system health. As Hameedi et al. note, excessive amounts of nitrate and other forms of reactive nitrogen remain of greatest concern due to their role in enhancing phytoplankton growth. This, in turn, may lead to algal blooms, oxygen consumption in seawater and on the seabed, altered patterns of primary productivity, changes in species composition, and shading effects on macrophytes and seagrass beds. Unfortunately, there is no shortage of estuaries, large or small, affected (e.g., Gulf of Mexico, Chesapeake Bay). The integrated modeling approaches being used today to evaluate the larger systems are some of the most complex undertaken by the community to date.

Atmospheric Deposition of Mercury

It is estimated that atmospheric mercury has increased roughly three-fold since the beginning of the Industrial Revolution.[10] A decade ago, the combustion of fossil fuels and waste materials accounted for 87% of all anthropogenic mercury emissions within the United States.[11] Another 10% was attributed to manufacturing, with most of that coming from a handful of industries (e.g., chlor-alkali, Portland cement, pulp and paper). In the 1990s, EPA's initial regulatory focus was placed on the control of mercury from municipal and medical waste incineration, which accounted for 29% of the known load. With the Clean Air Mercury Rule of 2005, EPA has since turned its focus to further control of mercury emissions from oil (7%) and coal (46%) consumption.[11] While emissions have recently decreased in Europe and North America, and are expected to continue to follow this trend, mercury emissions in Asia have been increasing rapidly, now accounting for 50% of global emissions.[10]

On page 26, Knightes et al. detail the interconnected processes that determine how mercury moves into and out of air, soil, sediments, water, and biotic mediums. Capable of traveling even greater distances than sulfur and nitrogen, elemental (neutral Hg^0, oxidized Hg^{2+}) and particle-bound (Hg_p) mercury also find their way back into the ecosystem through wet and dry deposition. Predominantly found in its neutral state (Hg^0) in the air, the majority of mercury is oxidized (i.e., Hg^{2+}) when in water, sediments, and soils.[12,13] A small fraction of this pool of divalent mercury is transformed by microbes into methylmercury,[14] where it biomagnifies in aquatic food webs.[15] As a result, methylmercury concentrations in higher trophic level organisms, such as piscivorous fish, birds, and wildlife, are often 10^4 to 10^6 times higher than aqueous concentrations.[14] The predominant concern for environmental managers, so far, has been degraded human health tied to nervous and reproduction system effects associated with methylmercury exposure via consumption of fish and other marine life.

Managing Land and Freshwater

Pollutants may be released to the air, water, or land surface from numerous sources, such as landfills, power plants, underground storage tanks, mining operations, industrial manufacturing facilities, agricultural fields, and various silvacultural, horticultural, and aquacultural activities. There are also a wide variety of introduction points for pollutants across residential and urban landscapes. Once released, these pollutants tend to disperse widely throughout the environment due to physical forces, such as wind, rain, erosion, and stream flow. Associated contaminants of heavy metals and organic chemicals may undergo various chemical and biological reactions that change their structure, which, in turn, may make them more or less toxic, and more or less mobile. The outcome is often an appreciable distribution of contaminants across several media (i.e., air, soil, groundwater, surface water, sediments, and biota). During their travels through the environment, wildlife or humans may be exposed. As example pathways of exposure, human and ecological receptors may ingest contaminated soil, food, or water, breathe contaminated air, or the contaminant may, through opportunities for contact, enter their body directly through the skin.

For releases with low-level contaminant concentrations, it is no longer obvious or intuitive as to which media/pathway/receptor exposure profile is of greatest concern. Integrated modeling has gained an increasing role in helping decision-makers identify the key profiles of concern, along with acceptable parameters needed to achieve sustainable protection of all receptor groups and associated subpopulations. On page 33, Mohamoud et al. describe the emphasis today in both assessment and regulatory management of the complex interactions between the hydrologic cycle and land use changes associated with urbanization and agriculture. The authors focus on how these play a key role in the generation and transport of contaminants leading to freshwater pollution, and how land uses can inherently change the physical response of the system to forcing functions of the hydrologic cycle (e.g., impervious cover).

Ecological Forecasting at Management Scales

On page 36, Mathur et al. note that there is added emphasis today at state and federal levels to develop increasingly sophisticated ecological forecasts at watershed and regional scales. The general problem faced is the need to establish effective strategies for reducing the impacts of a range of human activities, as well as mitigating extreme natural events. Solutions call for adaptive assessment and management frameworks that can better optimize integrated knowledge and data across the chemical, biological, and physical sciences, which underpin terrestrial and aquatic ecosystems. The front-end stressors and back-end valued endpoints also need to be directly assembled into the decision framework (Figure 1).

Such efforts are increasingly geared to directly integrate assessment capabilities with socio-economic valuations (i.e., ecosystem services). The end-goal is to arrive at "turn-key" decision support systems that can deliver and sustain maximal ecosystem productivity (e.g., fisheries, forests, recreation). It's not a new idea, but it is gaining renewed support across many key research organizations today. In other words, we are attempting to evaluate and rank the effects of sulfur, nitrogen, and mercury emissions; simultaneously determine how global warming may affect outcomes; and place this in context of how to best manage a wide range of other point and nonpoint sources of pollution associated with pathogens and sediments, pesticides, heavy metals, and commercial and industrial organic chemicals. While these efforts will, out of necessity, initially limit themselves to the evaluation of a few simple combinations of stressors, dealing with "the whole nine yards" is the end-goal of these multidisciplinary integrated decision-making frameworks.

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MANAGING THE MULTIMEDIA FUTURE

A common idea underpinning multimedia problem statements is that comprehensive solutions to complex problems are needed for effective cost-benefit analyses. However, it is likely that complex analysis will verify that a suite of relatively simple solutions can solve our problems. For today's multidimensional problems, it becomes a matter of figuring out which combination of levers to move and how much to move each one to get the job done. Indeed, a major task facing developers of multidisciplinary integrated decision-making frameworks is to account for the complexities of the system under study, while at the same time maintaining the simplicity and transparency in model form that decision-makers and stakeholders demand. These two key attributes of modeling systems have been and can continue to be a recipe for success.

Defining our future challenges and needs for enhanced integrated modeling for decision-making across local to global scales, world energy consumption is projected to increase 57% from 2004 to 2030.[16] This assumes a regulatory status quo worldwide. As such, coal consumption is projected to increase 74%, where China and India alone will account for 72% of the increase.[16] Tied closely to worldwide trends in fossil-fuel-based energy production and consumption, along with noted problems for sulfur and nitrogen, the familiar expression that "mercury is on the rise" becomes increasingly profound on several fronts. As the world's burn-rate increases, associated emissions of CO_2 tied to global warming are anticipated to also increase. If not mitigated by appropriate controls, local and regional problems associated with nitrogen and sulfur, and local, regional, and global problems associated with mercury and CO_2 can only be expected to be increasingly problematic. The correlation of these trends to further increases in other organic and inorganic carbon-based chemicals in the environment provides a compelling argument that we should significantly expand capacity across the environmental community to both enhance multimedia modeling and secure its marriage to informed decision-making. **em**

REFERENCES

1. *Implementing International Agreements on Persistent Organic Pollutants (POPs): Proposed Amendments to the Toxic Substances Control Act*; Resources, Science, and Industry Division, Report for Congress RL33336; Congressional Research Service, Library of Congress, Washington, DC, 2006.
2. Perfluorooctanoic Acid (PFOA), Fluorinated Telomers; Request for Comment; EPA, OPPT–2003–0012; FRL–7303–8; *Fed. Regist.* **2003** *68* (73), 18626-18633.
3. Kelly, B.C.; Ikonomou, M.G.; Blair, J.D.; Morin, A.E.; Gobas, F.A.P.C. Food Web–Specific Biomagnification of Persistent Organic Pollutants; *Science* **2007**, *317* (5835), 236-239.
4. Arnot J.A.; Gobas, F.A.P.C. A Food Web Bioaccumulation Model for Organic Chemicals in Aquatic Ecosystems; *Environ. Toxicol. Chem.* **2004**, *23* (10), 2343-2355.
5. Scheringer, M.; Wania, F. Multimedia Models of Global Transport and Fate of Persistent Organic Pollutants. In *Persistent Organic Pollutants: Environmental Behaviour and Pathways of Human Exposure*; Harrad, S., Ed.; Kluwer Academic: Boston, MA, 2003; p. 237-269.
6. McKone, T.E.; MacLeod, M. Tracking Multiple Pathways of Human Exposure to Persistent Multimedia Pollutants: Regional, Continental, and Global-Scale Models; *Annu. Rev. Environ. Res.* **2003**, *28* (1), 463-492.
7. Mackay, D.; MacLeod, M. Multimedia Environmental Models; *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management* **2002**, *6* (2), 63-69.
8. Hertwich, E.G.; McKone, T.E.; Pease, W.S. A Systematic Uncertainty Analysis of an Evaluative Fate and Exposure Model; *2000 Risk Anal.* **2000**, *20* (4), 439-454.
9. Whitall, D.; Casstro, M.; Driscoll C. Evaluation and Management Strategies for Reducing Nitrogen Loading to Four U.S. Estuaries; *Sci. Total Environ.* **2004**, *333*, 25-36.
10. Selin, N.E. Mercury Rising: Is Global Action Needed to Protect Human Health and the Environment? *Environment: Science and Policy for Sustainable Development* **2005**, *47* (1), 22-35.
11. *Mercury Study Report to Congress*; EPA-452/R-97-005; U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Washington, DC, 1997.
12. Lin C.-J.; Pehkonen, S.O. The Chemistry of Atmospheric Mercury: A Review; *Atmos. Environ.* **1999**, *33* (13), 2067-2079.
13. Morel, F.M.M.; Kraepiel, A.M.L.; Amyot, M. The Chemical Cycle and Bioaccumulation of Mercury; *Annu. Rev. Ecol. Syst.* **1998**, *29*, 543-566.
14. Jackson, T.A. Mercury in Aquatic Ecosystems. In *Metal Metabolism in Aquatic Environments*; Langston, W.J., Bebianno, M.J., Eds.; Chapman & Hall: London, UK, 1998; p. 97-159.
15. Kidd, K.A.; Hesslein, R.H.; Fudge, R.J.P.; Hallard, K.A. The Influence of Trophic Level as Measured by Δ15N on Mercury Concentrations in Freshwater Organisms; *Water, Air, Soil Pollut.* **1995**, *80*, 1011-1015.
16. International Energy Outlook—2007; DOE/EIA-0484(2007); U.S. Department of Energy, Office of Integrated Analysis and Forecasting, Washington, DC, 2007.