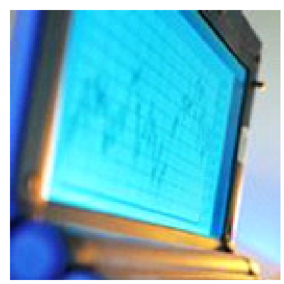
EPA 100/R-08/010

Integrated Modeling for Integrated Environmental Decision Making



White Paper

November 2008

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"Despite its complexity, for pollution control purposes, the environment must be perceived as a single, interrelated system"*

* Reorganization Plan No. 3 of 1970 to establish the Environmental Protection Agency, U.S. Code, Congressional and Administrative News, 91st Congress--2nd Session, Vol. 3, 1970

FOREWORD

Building bridges among the different modeling communities is, in my view, essential for the future of environmental protection. Happily, our models are improving: as computing capacity continues to grow, our ability to use models to predict environmental outcomes should also increase. This will always depend, of course, on our ability to have good input data: modelers should be the most vocal advocates for empirical sampling. Modeling and monitoring are complementary, not competing, needs.

The reason why this bridge-building is essential, however, is that we need all of this increased capability to see more clearly what we've always known in principle: that the environment is an interconnected system, and that what happens in one location can have repercussions far away. Just to cite three examples, the interfaces between air and water models become more and more important when you are looking at highly restrictive total maximum daily loads in particular watersheds, or when you are looking at aerosol transport from animal waste lagoons as a factor in fine particle attainment, or when you are trying to make critical judgments about the relative importance of global cycle vs. locally generated mercury in assessing control strategies for particular ecosystems. The answers which models will give to these questions will drive billions of dollars in pollution control costs. More importantly, getting the answer right will literally be a life and death matter for some people, and for sensitive and vulnerable ecological systems.

We won't advance this science if everyone stays in their stovepipes, which I suspect can be as real in the modeling arena as in all other aspects of human endeavor.

Stan Meiburg
National EPA-CDC Liaison
Deputy Regional Administrator, Region 4
January 16, 2007

In supporting the Agency's regulatory agenda, we are often asked to deliver technical products that assist decision makers in more fully understanding the interplay between environmental condition, existing and prospective mitigation measures, and the various benefits they are projected to yield our society. The delivery of such analyses is made all the more difficult when fate, transport, exposure, risk, and economic models, and the modeling communities who exercise them, function in isolation one from the other. The Agency can and should do better in delivering the integrated modeling needed to energize integrated decision making.

There is reason for optimism, seen in two examples where project teams are attempting to integrate multiple models to arrive at more complete, seamless assessments of environmental impact. First, we are seeing real interest in tacking food web models onto the tail end of water quality models (i.e., integrating food web and fate/transport models). This approach would use the prediction of bioaccumulative pollutant concentrations in water and sediment to render a subsequent prediction of fish tissue concentration at the top of the food chain. Since our typical water quality model frameworks do not include a food web algorithm, scientists are left to figure out how best to configure two independent modeling frameworks so they effectively "speak" to one another.

The second example involves air toxics modeling projects. Investigators are working on linking air toxics monitoring and modeling studies conducted by one group with the extensive human exposure studies conducted by another group. Their challenge is exceedingly difficult: to produce scientifically compelling and pragmatic linkages between fate and transport, human exposure, risk, and/or economic models where few such connections currently exist.

"Doing" model integration inevitably involves an ever-widening circle of subject matter experts, from the scientific and programmatic arenas alike. To be sure, bigger conference rooms are needed to accommodate all the individuals from all the disciplines. But far more expansive, integrative thinking on the part of our best and brightest is the critical key to our success. Understanding how all of the components fit, how to optimize system performance and characterize resultant uncertainty is a tremendous challenge worthy of our concerted effort.

Ron Kriezenbeck
Deputy Regional Administrator, Region 10
Co-Chair, Council for Regulatory Environmental Modeling
January 23, 2007

It has become apparent that in order to address most environmental problems today, an integrated modeling approach is needed to understand the fate and transport of pollutants across media and develop sound management plans. In the past, we have traditionally developed very complex models for single media without consideration to integrating these models across multiple media. However, as resources diminish and emerging issues arise and multiply, we must focus on early coordination across all our programs to ensure that efforts are not duplicated and that models cannot only be easily integrated, but also used for multiple purposes.

The concept of "integrated modeling" is a broad term that our Region interprets in multiple ways. From a watershed-based perspective, we have applied integrated modeling in developing land-based loadings to surface waters and then modeling the fate and transport of these pollutant loads using a water quality model. This modeling framework has allowed our decision makers to evaluate the impact of varying pollution controls to achieve environmental goals.

Over the past several years, with the need to address complex water quality problems associated with legacy and atmospheric pollutants, watershed modeling has further expanded to fate and transport modeling across multiple media. Legacy pollutants, such as PCBs, require an integrated modeling framework that includes fate and transport models for sediment, water and biota. Developing these models requires extensive resources, which are not always available. Similarly, the development of pollution control plans for atmospheric pollutants (e.g., acid rain) also requires an integrated modeling approach. The difficulty in developing these models is not only the resources, but also the need to coordinate and understand the modeling frameworks in multiple media.

Finally, as our understanding of complex environmental problems evolve, and the models we construct to assist us with our regulatory decision making often expand in their complexity, scope and breadth to encompass these emerging issues and insights, we must avoid the tendency to develop overly complex models that are not only resource intensive to run, but which can only be used by a select number of individuals. Region 2 remains thankful to the CREM for their continued efforts to identify and address the Agency's modeling needs, and I commend them for their initiative in convening this workshop to craft a strategic framework to incorporate integrated modeling into EPA decision making.

Kathy Callahan
Deputy Regional Administrator, Region 2
January 25, 2007

The Office of Air and Radiation, of which our Office is a part, has a strong history of supporting the development and application of integrated models and approaches. Like other program offices, these models and approaches are critical in informing the decision making process, providing legal justification for regulatory action, and complying with legislative and administrative requirements (e.g., cost-benefit assessment). Our partnership with the Office of Research and Development (ORD) and the scientific community across multiple disciplines provides the scientific credibility and transparency required for our regulatory and policy assessments of air pollution issues. For example, with ORD we sponsor the Community Modeling and Analysis System (CMAS) Center that supports community-based air quality models including the Community Multi-scale Air Quality (CMAQ) model.

The technical assessment conducted for our Clean Air Mercury Rule (CAMR) provides an excellent example of the importance of an integrated approach to inform regulatory action[1]. For this rule, we linked several complex models to address the cycle of mercury in the environment and to predict the impacts of the CAMR rule. Our integrated approach was able to take individual elements – which are themselves complex -- and analyze them as links in a chain. We evaluated the chain of mercury deposition to waterbodies to fish tissue concentrations and the associated human exposures and risks. These models, for example, included the Integrated Planning Model (IPM) that characterized utility boilers, their mercury emissions, and costs of control as well as the CMAQ model that predicted the mercury deposition across the continental US. The need for and demands on integrated models and approaches will be increasing as we move forward to address even more complex air quality problems such as secondary formation of fine particulates, atmospheric deposition effects on ecosystems, and climate-air quality linkages.

Steve Page
Director, Office of Air Quality Planning and Standards
Office of Air and Radiation
January 25, 2007

[1] On February 8, 2008, the U.S. Court of Appeals for the District of Columbia Circuit vacated the Clean Air Mercury Rule, for reasons unrelated to the modeling conducted in support of the rule.

EXECUTIVE SUMMARY

The need for cost-effective, harmonious and equitable solutions to environmental protection and management challenges drives the call for the adoption of sound holistic analysis that reflects the inherent complexity and interconnectedness of environmental systems. The major challenge facing environmental protection today—whether one articulates it in terms of sustainability, cumulative risk, valuation of ecosystem services or community-based environmental protection—is to eschew the single chemical-single medium-single pathway view that existing environmental statues have fostered, in favor of a view of organisms and the environment as they really are: an integrated whole.

Integrated modeling is a systems analysis-based approach to environmental assessment that includes a set of interdependent science based components (models, data, and assessment methods) that together form the basis for constructing a modeling system capable of simulating environmental systems relevant to a well specified problem statement. This approach is useful for a wide spectrum of environmental assessment and management needs, including providing better conceptual understanding of the interconnectedness among the components of the environmental system, as well as in the prospective and retrospective assessment of policies. The concepts related to integrated modeling are appreciated and applied by a growing majority of the environmental science based community within and outside the Agency. Yet the realization of the benefits of this approach is hampered by a number of challenges, including the lack of a community wide interchange and consistency and harmonization across these various efforts. As integrated modeling projects continue to operate in isolation, there is a limited ability to produce reusable and interoperable tools and methods, and the result is less cost effective and less consistent from a science perspective.

This white paper aims to lay the foundation for the consistent and systematic implementation of integrated modeling approaches and practices that inform Agency decision making, at both the strategic and tactical levels. By adopting a systems approach, the goal is to facilitate better problem conceptualization, analysis of multimedia fate and transport of pollutants, assessment of cumulative exposure and risk, development and comparison of policy options and the holistic determination of the likely impacts of alternative management actions and policies. Furthermore, the goal of integrating modeling into decision making is to achieve a process that results in significant improvement in our decision effectiveness and enhances stakeholder collaboration and decision making transparency. By pursuing an organization-level approach to integrated modeling, the goal is to promote consistency and repeatability of analyses.

This white paper recommends a commitment to a new direction in environmental modeling and decision making, one that adopts a systems thinking approach. If the recommended actions proposed here are adequately funded and supported, we will be able to significantly improve our ability to conduct scientific analyses in support of integrated decision making and to help ensure EPA implements efficient, effective and equitable policies and programs to advance environmental protection as well as economic prosperity. The Strategic Vision and Action Plan proposed in this white paper provide a holistic response to the science, technology and organizational challenges facing the consistent implementation of integrated modeling in EPA by creating an enabling environment that will:

- Promote better understanding of integrated modeling, its purpose, utility and applicability;
- Raise the profile of integrated modeling, and communicate its importance to Agency upper management;
- Develop infrastructures that enhance interoperability among information sources, including models and data;
- Implement mechanisms that enhance communication, coordination, collaboration and knowledge sharing among stakeholders (i.e. scientists, modelers, risk assessors, decision makers and affected stakeholders);
- Promote more consistent modeling and analysis across EPA offices;
- Foster an enhanced analytical ability to characterize, communicate and understand uncertainties associated with integrated modeling and the implications of these uncertainties for decision making;
- Enable more transparent decision making supported by objective sound scientific analysis.

The action plan focuses on providing an outline of the requirements for establishing an organization-level solution to facilitate a concerted, systematic, and stable approach to the development and application of integrated modeling at EPA. Success of the action plan relies on the direct support and involvement from Agency leadership, involvement from across the community of stakeholders, direct relevance of the plan and its products to actual regulatory decisions, and accountability for development of the specific products.

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This document is a product of a collaborative development process involving contributors from across EPA's offices.

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TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

1.1 Strategic Vision of Integrated Modeling for Integrated Environmental Decision Making

Many white papers start with descriptions of the problem; this one begins with a vision. The vision involves EPA's response to the increasingly complex needs for environmental systems analysis ranging from multi-media contaminant exposure and risk assessment to regional scale land-use management to ecosystem services valuation to global climate and finally to the concept of environmental sustainability.

The vision is of a future where EPA policies and activities are adaptive, collaborative and innovative. Decisions are informed using data, models, and assessments that are specifically developed to describe and forecast the integrated behavior of the environment in response to natural and human induced stress. This integrative systems approach is based on sound science and engages stakeholders throughout the process. Information is provided in a consistent manner across regulatory statutes, with full transparency and articulation of uncertainties. Individual stressors, important in one regulatory context, are evaluated in the context of co-occurring stressors, thus focusing on the total burden carried by the environment and minimizing the transfer of environmental problems from one regulatory context to another. Opportunities for trade-offs among stressors are recognized and the potential for simply transferring stress from one regulatory context to another is minimized. Environmental impact analyses for forecasting and source allocation are also available. The community of environmental stakeholders and associated organizations invest in the co-development of computer-based technologies that facilitate a collaborative approach to both integrated environmental science and decision support. This integration-oriented approach will help to enhance the transparency and scientific credibility of future environmental management decisions.

1.2 Drivers for Change: Why does EPA need this vision?

The creation of the US Environmental Protection Agency in 1971 acknowledged the imperative for an integrated environmental management approach; one that perceives the environment as "a single, inter-related system" and "effectively ensures the protection, development and enhancement of the total environment."[2] While it is clear that in the 36 years since its inception, the EPA has achieved remarkable environmental progress through its air, water, toxics and land programs, it has struggled to deal with the environment as a single interrelated system[3]. Analysts point to the disconnect between the manner in which EPA programs are organized and the fluid interconnectedness among pollutants and their

[2] Reorganization Plan No. 3 of 1970 to establish the Environmental Protection Agency, U.S. Code, Congressional and Administrative News, 91st Congress--2nd Session, Vol. 3, 1970

[3] Hecht, A. D. and Sanders, W.H (2007) How EPA Research and Programs Can Advance Urban Sustainability, draft

environmental consequences across all media[4]. This dichotomy presents a significant challenge for scientists and decision makers to both develop effective and efficient environmental protection strategies as well as to understand and communicate environmental outcomes. In fact, a recent GAO report concerning challenges at EPA noted that environmental programs may not yield measurable results for many years into the future[5]. Among the report recommendations in terms of measuring the results of EPA programs was the need to take a holistic or "systems" approach to the problem being addressed[6]. Furthermore, the National Academy of Public Administration (NAPA) identified the complex environmental problems involving point and non-point source pollution as some of the major challenges facing EPA. The report concluded that to achieve national goals to improve ambient environmental conditions, EPA should take a leading role in mobilizing multiple programs, federal agencies, state and local government and other parties[7]. Consequently, as EPA continues to focus on achieving favorable environmental outcomes and improved program efficiencies, developing a more holistic understanding of the environment and the mechanisms governing multimedia fate and transport of pollutants, as well as the multiple exposure pathways and resultant responses of humans and ecosystems, is crucial to the Agency's ability to assess and protect our environment in the future. There is a growing consensus, both within and outside the Agency, that an integrated systems approach to environmental management is required now more than ever. Such an approach, rooted in the principles of sustainability, will result in greater environmental benefits and ensure that significant and ever more complex environmental problems are adequately identified, assessed and addressed (see Box 1.1).

Box 1.1 An Evolving Perspective: Environmental Systems Analysis and Sustainability

"The whole is more than the sum of the parts"

--Aristotle

A system is a group of interacting, interrelated and interdependent components that form a unified whole[8]. Instead of the traditional approach that considers separate parts of a larger system, systems-thinking takes a more holistic analytical approach and emphasizes the relationships among a system's parts. Experience has shown that applying a systems approach results in significant improvement in effectiveness as well as understanding[9]. Environmental systems analysis is the application of systems analysis in the environmental field to describe and analyze the causes, mechanisms, effects of, and potential solution for specific environmental problems. Environmental systems analysis acknowledges the complexity of environmental systems and encourages more long-term analysis to include consideration of unintended consequences and to avoid shifting of problems. Through environmental systems analysis, the aim is to understand the dynamics, processes and functional relationships within environmental and

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[4] USEPA Office of Inspector General (2006) Studies Addressing EPA's Organizational Structure, Report No. 2006-P-00029, Washington, DC
[5] GAO (2001) Major Management Challenges and Program Risks: Environmental Protection Agency, GAO-01-257, Washington, DC
[6] GAO (2004) Environmental Indicators: Better Coordination Is Needed to Develop Environmental Indicator Sets That Inform Decisions, GAO-05-52, Washington, DC
[7] National Academy of Public Administration (2007) Taking Environmental Protection to the Next Level: An Assessment of the U.S. Environmental Services Delivery System, Washington, DC
[8] http://www.thesystemsthinker.com/systemsthinkinglearn.html
[9] Chapman, J. (2004) System Failure, 2nd edition, Demos, London, UK

anthropogenic systems to provide a sound basis for management decisions. Systems analysis supports the development of integrated policy and action. This integrated approach has a number of advantages; it prevents shifting of environmental problems, leads to higher environmental yields and is more efficient and thus usually more cost-effective[10]. Thus over time, integrated decision making would ensure EPA implements efficient, effective and equitable policies and programs to advance environmental protection as well as economic prosperity.

An example of the EPA's move to a new paradigm away from pollution control and prevention to systems analysis and sustainability, is the development of the EPA Sustainability Research Strategy, which was recently reviewed and endorsed by the EPA Science Advisory Board. The Sustainability Research Program "aims to improve understanding of the earth's natural and man-made systems, assess threats to those systems, design and apply innovative and cost-effective industrial practices and develop and apply new technologies and decision support tools"[11]. As part of the Agency's response to the SAB, the Agency committed to implement a number of demonstration projects which adopt a broader, system-based perspective. These projects may include studies of biofuels policies and impacts of biofuels production on the environment and the hypoxic environment in the Gulf of Mexico and Chesapeake Bay[12].

This white paper focuses on one component of the scientific and economic analyses underpinning environmental decision making: computational modeling. The movement to integrated modeling is driven by the need to expand beyond single-media studies and analyses, gain greater understanding of complex processes and interrelationships and develop long-term cost-effective strategies. This does not mean that single media, single pollutant, and single pathway assessments are no longer part of the environmental protection landscape; they are. However, their place and role in the landscape is being greatly reduced as the new wave of problems that require an integrative systems analysis approach gain priority attention. As will become clear in this white paper, the benefits of integration in modeling and decision making are significant. Given the complexity of the environment, integrated models are needed to inform decisions that invariably impact competing interests. Just as modeling has become an indispensable source of information for environmental decision making, integrated modeling is critical to holistic and systems analysis. While there has been some experience in the development of integrated modeling applications, this has primarily occurred on an *ad hoc* and piecemeal basis, with limited consistency and harmonization. Increased integration is impeded by a number of scientific, technological and organizational challenges and it has become clear that robust progress in this area requires high-level agency commitment, involvement and support. Faced with the reality of working within declining or limited resources, EPA needs to transcend the current stove-piped *status quo* and move forward with a

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[10] Sliggers, Jo. (2004) The need for more integrated policy for air quality, acidification and climate change: reactive nitrogen links them all, Environmental Science and Policy, 7, 47-58

[11] Office of Research and Development's (ORD) Sustainability Research Strategy - DRAFT (PDF). June 13, 2007 http://www.epa.gov/sustainability/pdfs/sustainability-research-strategy-draft061307.pdf

[12] Agency Response to the Advisory on the Office of Research and Development's (ORD) Sustainability Research Strategy and the Science and Technology for Sustainability Multi-year Plan (EPA-SAB-07-007): http://www.epa.gov/sab/pdf/sab-07-007_response_08-03-07.pdf

coordinated strategy to implement integrated modeling activities that inform both program operations and EPA strategic planning.

1.3 Background and Purpose of this Document

In its response to a Science Advisory Board Panel review[13] of the Draft Guidance on Environmental Models[14] and Models Knowledge Base, the EPA committed to implementing a series of activities to continue providing a venue for intra-agency coordination on modeling issues and fostering a more integrated approach to modeling in environmental decision making[15]. This white paper builds on the first of these activities, a highly successful workshop organized by EPA's Council for Regulatory Environmental Modeling and the ORD National Exposure Research Lab's Ecosystems Research Division. This workshop, held at the EPA campus in Research Triangle Park, NC, during the period of January 30-February 1, 2007, aimed to initiate a broad-based dialogue on the use of integrated modeling approaches to inform environmental decision making. The workshop brought together over 150 participants from EPA's Core (ORD, OEI, OPEI), Program and Regional Offices. Attendees included decision makers, modelers, data experts and risk assessors. Participants and invited speakers also came from other Federal Agencies (NASA, USDA, OMB), academia and international organizations (Environment Canada and the European Union). The workshop agenda addressed decision making drivers for integration, associated science and technological approaches and interoperability challenges. Through a mix of high-level panel discussions, invited case-study and technical presentations and break-out discussion sessions, the workshop participants identified emerging modeling priorities and discussed the development of a strategic vision for implementing integrated modeling in a consistent, coherent and collaborative fashion to inform decision-making at EPA. The results workshop reflected three familiar and fundamental values:

- *Sound science*: The ongoing pursuit of a better understanding of how the natural world and our health are affected by what we extract from and return to the environment.
- *Practical outcomes*: The delivery of tools that squarely match the needs of decision makers.
- *Cost-effectiveness*: The best use of taxpayer dollars and human talent available.

The workshop participants also identified the scientific, technological and organizational challenges that need to be overcome for us to attain this vision.

This white paper attempts to present a foundation for the consistent and systematic implementation of integrated modeling approaches and practices can inform Agency decision-making, at both the strategic and tactical levels. By adopting a systems approach, the goal is to facilitate better problem

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[13] SAB report: http://www.epa.gov/sab/pdf/sab_06_009.pdf
[14] CREM draft Guidance: http://www.epa.gov/ord/crem/library/CREM%20Guidance%20Draft%2012_03.pdf
[15] EPA Administrator's response: http://www.epa.gov/ord/crem/library/SAB-SAB-06-009_Response_21-01-06.pdf

conceptualization, the analysis of multimedia fate and transport of pollutants, assessment of cumulative exposure and risk, the development and comparison of alternative policy options, and the holistic determination of the impacts of various management actions and policies. Furthermore, the goal of integrating modeling into decision-making is to achieve a process that results in significant improvement in problem understanding and solution effectiveness as well as enhancing stakeholder collaboration and decision-making transparency. By pursuing an organization-level approach to integrated modeling, the goal is to promote consistency and repeatability of analyses. The objectives of this white paper are to:

- Outline the need for and value of integrated modeling for EPA science and decision-making;
- Analyze the state of the art and practice of integrated modeling and include examples of how this approach has been successfully applied and the lessons learned;
- Identify the challenges to more fully implementing this approach in the future; and
- Present a plan to implement the Strategic Vision for integrated modeling for integrated environmental decision-making that outlines the necessary actions needed to create an enabling environment to support the development and implementation of integrated modeling systems for integrated decision making.

1.4 Intended Audience

While it is anticipated that this document would be of relevance to the work of a diverse range of audience in EPA's offices, it particularly echoes the vision and direction of a number of existing and developing EPA efforts that aim to foster a more integrated, holistic and strategic approach to EPA activities. These efforts includes, but are not limited to: the Sustainability Research and Ecological Research Programs in ORD; the Advanced Monitoring Initiative projects supported by the EPA Group on Earth Observations; ORD's Global Change Air Quality Assessment, which is evaluating the impacts of global changes on future air quality and developing decision support information and tools for national, regional and state-level environmental planners; the Office of Water's adoption of a watershed approach to water resources management and more recently its work to develop a National Water Program Climate Change Strategy; the Office of Air's support for a multi-pollutant air quality management approach that integrates air quality planning with growth planning and brings land use, transportation, energy and climate change considerations into air quality management; the Integrated Permitting work in OPEI's National Center for Environmental Innovation; and the Office of the Chief Financial Officer, specifically for their work in Agency Strategic Planning. In addition to incorporating comments from the workshop discussions of the workshop, this white paper includes inputs from staff from across the Agency.

CHAPTER 2: INTEGRATED MODELING

2.1 What is integrated modeling?

Environmental decision-making often relies on analysis of quantitative information from both monitoring and modeling to support assessments of both the state of the environment and the consequences of alternative environmental policies (Figure 1). Models represent our understanding of how the world works and play an important role in the conduct of both research and regulatory decision-making. In the conduct of research, models facilitate the development and testing of our understanding, while in the context of decision-making, models provide a means for applying our understanding to solve real world problems. Models and observation data are interdependent. Observation data alone cannot provide a complete picture; models are necessary for prediction purposes as well as for exploring conditions not encountered or measurable in the field. Yet, observation data provide the basis for model development and refinement, parameter estimation and corroboration of model results. Models can also be used to iteratively refine monitoring plans and guide selection of monitoring sites. Models, by their very nature, are integrative, that is, they represent a means for expressing the interdependent influences and behaviors of multiple components, mechanisms and processes, e.g., chemical fate and transport in the atmosphere and transfer to surface waters.

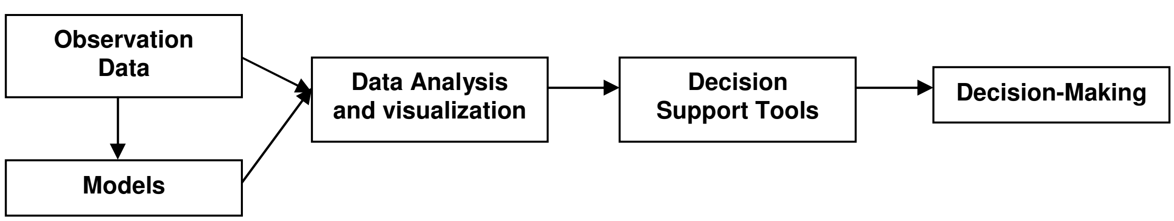

Figure 1: Analytical process to support decision making

2.1.1 The evolution of integrated modeling at EPA

To appreciate the increasingly complex nature of integrated modeling, it is helpful to review the history of environmental assessment at EPA. Figure 2 presents a historical view of the key characteristics of environmental assessments conducted in support of EPA regulatory decisions.

In the early years at EPA, the principal environmental concerns related to human heath risks resulting from direct exposure to heavily contaminated media (air, water, soil). The sources of contamination were primarily the result of direct releases to a single medium of concern (e.g., atmospheric emissions, surface water discharges, spills to soils) and, while multiple chemicals may have been present, concern was primarily focused on a single compound based on a combination of its mass/volume of release, its toxicity, and the understanding or assumption that implementing clean-up for the focus or worst compound would also take care of most other compounds as well. Modeling to support these regulatory assessments and decisions was therefore medium specific, involving a single exposure pathway (e.g., breathing contaminated air), and typically focused on the risk of carcinogenic effects to a hypothetical "maximally exposed individual." Models were deterministic and uncertainty analysis, if conducted, consisted of model calibration or simply a qualitative statement of sources of uncertainty and potential implications. Regulatory programs that emerged from these early years included: the National Ambient Air Quality Standards (NAAQS) and the National Emission Standards for Hazardous Air Pollutants (NESHAPS) in the Office of Air; the Total Maximum Daily Load (TMDL) and the National Pollutant Discharge Elimination System (NPDES) Toxics Monitoring Program in the Office of Water; and the Hazardous Waste Program in the Office of Solid Waste (i.e. hazardous waste identification). Each of these programs was primarily concerned with human exposures and associated risks occurring as a result of direct contaminant releases to air, surface water, and groundwater, respectively.

EARLY YEARS AT EPA Single Pathway Analysis	RECENT PAST/PRESENT Multiple Pathway Analysis	FUTURE Integrated Systems Analysis
Single Chemical	Multiple Chemicals, sediments	Mixtures, sediments, land use change, climate change
Multiple Chemical Sources	Multiple Chemical Sources	Multiple Chemical/Non-chemical Sources
Single Medium Fate & Transport	Linked Media Fate & Transport	Integrated Multimedia Fate and Transport with Mass Balance and Feedback
Single Exposure Pathway	Multiple Exposure Pathway Analysis	Integrated Exposure Pathway Analysis, Land Use Management
Cancer Risk to Maximally Exposed Individual (MEI)	Cancer/Non-cancer Risk Across Human Population Ecological Risk (Populations)	Aggregate Cancer/Non-cancer Risk across Human Population Ecological Risk (populations, communities), Ecosystem health and services evaluation
Deterministic Analysis	Probabilistic Analysis	Probabilistic Analysis, Adaptive Management Strategies
Model Calibration/Qualitative Uncertainty Analysis	Model Calibration/Qualitative and Limited Quantitative Uncertainty	Comprehensive and Fully Integrated Uncertainty Analysis

Figure 2: Evolving Regulatory Focus

Having addressed the major problems that motivated the formation of the Agency, the EPA then entered an era characterized by concerns related to indirect pathways of exposure. Through the process of regulatory development, including extensive public comment, it became clear that significant exposure and risk could occur via pathways other than contact with the medium within which a contaminant was released. It was increasingly recognized that contaminants released to one environmental medium (e.g., the atmosphere) could subsequently be transferred, as well as transformed, to other media (e.g., air emissions subsequently deposited on land and surface water) where additional pathways for exposure became active. Concern grew for non-carcinogenic health effects and also for potential impacts on ecological species and habitats. Increased emphasis was also placed on quantifying the uncertainty associated with assessments and to understand better the distribution of exposures and risks across the exposed populations. Modeling to simulate the multi-media fate and transport of pollutants, account for multiple exposure pathways, and implement emerging probabilistic approaches for risk assessment necessarily required higher levels of integration. It is during this later period, which continues to the present time, that "integrated modeling", as referred to in this paper, emerged as a new concept.

At this new scale of integration, the science, technology, and organizational boundaries related to environmental modeling began to expand dramatically. On the science front, integration required a shift to a systems analysis approach and the resolution of issues related to information sharing across disciplines (e.g., how atmospheric science would be merged with surface water science to form an integrated model that included the dynamic exchange of contaminants between air and water). Also, data requirements increased dramatically and the need to more easily access data and ensure data quality and consistency across disciplines became increasingly evident, and in some cases mandated. Perhaps no area experienced more of an impact than modeling technology. Integrated modeling in this era saw the emergence of sophisticated Geographic Information Systems (GIS) and modeling infrastructures. Using location as an integrating concept, GIS allowed disparate sources of spatial data to be accessed, processed, and displayed in a manner that facilitates integrated assessments. Modeling infrastructures were designed and developed to inter-relate science models and to facilitate their integrated execution, as well as the visualization and interpretation of results.

Organizationally, EPA and the environmental protection statutes were structured to address the first level of integration, i.e., around individual environmental media. The regulatory programs mentioned previously matured with integration. The NESHAPS program developed a modeling based assessment approach that included pollutant fate and transport in all media and exposure and risk to humans and ecological species as a function of all relevant pathways. The TMDL program grew to include non-point sources of pollution, and thus integrated watershed modeling with surface water quality modeling to achieve its regulatory mandate. The Hazardous Waste Program expanded from a groundwater to drinking water well analysis to a full multi-media exposure and risk assessment methodology for land based waste disposal problems. There are many examples as well of how simply addressing uncertainty in historical regulatory programs itself represented a new age of integration to be dealt with and mastered. These are but a few examples of an Agency-wide evolution to address more complex problems that require more complex and integrated assessment methods and solutions.

The future is anticipated to follow the same trajectory, that is, the extent of problem complexity and required assessment model integration will continue to increase. Specifically, emerging problems related to regional scale land use management, impacts of global climate change, valuation of ecosystem services, the fate and transport of nanomaterials and life cycle analysis will clearly require further refinements of the science, technology, and organizational methods currently being established for integrated modeling. A paradigm shift, driven by the need to integrate and apply our collective knowledge of the environment, is occurring, and a more holistic approach to environmental systems analysis will be the result.

2.1.2 A working definition of integrated modeling

"Every definition is dangerous"
- Desiderius Erasmus

With the preceding background we can formulate a working definition of the term "integrated modeling". Even so, while definitions are useful in providing a common basis of understanding, establishing a firm definition of integrated modeling is problematic and may not capture the full essence of the concept. It is important to keep in mind that, as a concept, "integrated modeling" it can include a continuum or gradient of definitions, approaches and forms. **Fundamentally, integrated modeling is a systems analysis-based approach to environmental assessment. It includes a set of interdependent science based components (models, data, and assessment methods) that together form the basis for constructing an appropriate modeling system. The constructed modeling system is capable of simulating the environmental stressor-response relationships relevant to a well specified problem statement**. Integrated modeling reflects more a conceptual approach than a single, well defined collection of components. Thus, the actual science components necessary to address individual problems may vary in number and type. The following implementation characteristics of science-based modeling are important in all applications, and take on additional meaning and importance in the context of modern integrated modeling:

Coherence: Science components (data, models, methods and assumptions) are appropriately consistent across the system with respect to complexity (i.e., spatial, temporal, and scientific resolution of analysis), data requirements, and uncertainty.

Transparency: The science-based methodological approach is unambiguously clear with all assumptions, sources of data, model components, and results synthesis procedures documented.

Characterization of Uncertainty: Sources and propagation patterns of all factors that render a modeling-based result uncertain are systematically assessed, and clearly articulated and documented to the satisfaction of both science peers and decision makers.

Reproducibility: Related to transparency, reproducibility ensures that all stakeholders can efficiently recreate the integrated modeling approach and produce results identical to the original modeling effort.

Quality assured: Procedures and methods for assuring that the selected modeling approach is implemented without error are integrated directly into the modeling approach.

Comprehensive analysis of environmental issues generally requires integration of a number of components (Figure 3). Integrated modeling is not simply a model building exercise; it is a "participatory methodology that can be used for gaining insight over an array of environmental problems spanning a wide variety of spatial and temporal scales."[16] The integrated modeling process includes multiple layers of integration and environmental systems analysis:

- **Development of conceptual models:** Constructing integrated models requires that the important components within and affecting the system be identified and the relationships among these components be characterized. Development of such a conceptual model often requires dialog that transcends scientific and professional disciplines and can lead to a more holistic understanding of the problem at hand.
- **Representation of information:** Integrated modeling components often are developed by scientists and analysts in different disciplines, who may consider aspects of the problem on different spatial and temporal scales. Development of common data formats and underlying frameworks may facilitate interoperability, and can also yield improvements in the structure and flexibility of individual model components.
- **Support to decision makers:** In isolation, model developers may have the goal of representing the state of knowledge of science to the extent possible. Decision makers, however, are typically more interested in only understanding the dynamics of the system and possibly its response to particular prospective decisions or actions. Therefore, understanding the specific needs of the decision makers may result in a more efficient model building process and may produce results that more directly support decision-making.
- **Stakeholder involvement:** For integrated modeling systems to be developed to most effectively meet both the needs of scientists and decision makers, it is important that stakeholders be identified and engaged, incorporating their multiple sources of knowledge and information, identifying and mediating among their different priorities, and creating a shared vision.

[16] Risbey, J., Kandlikar, M., and Patwardhan, A. (1996). Assessing Integrated Assessments, Climatic Change, 34, 369-395

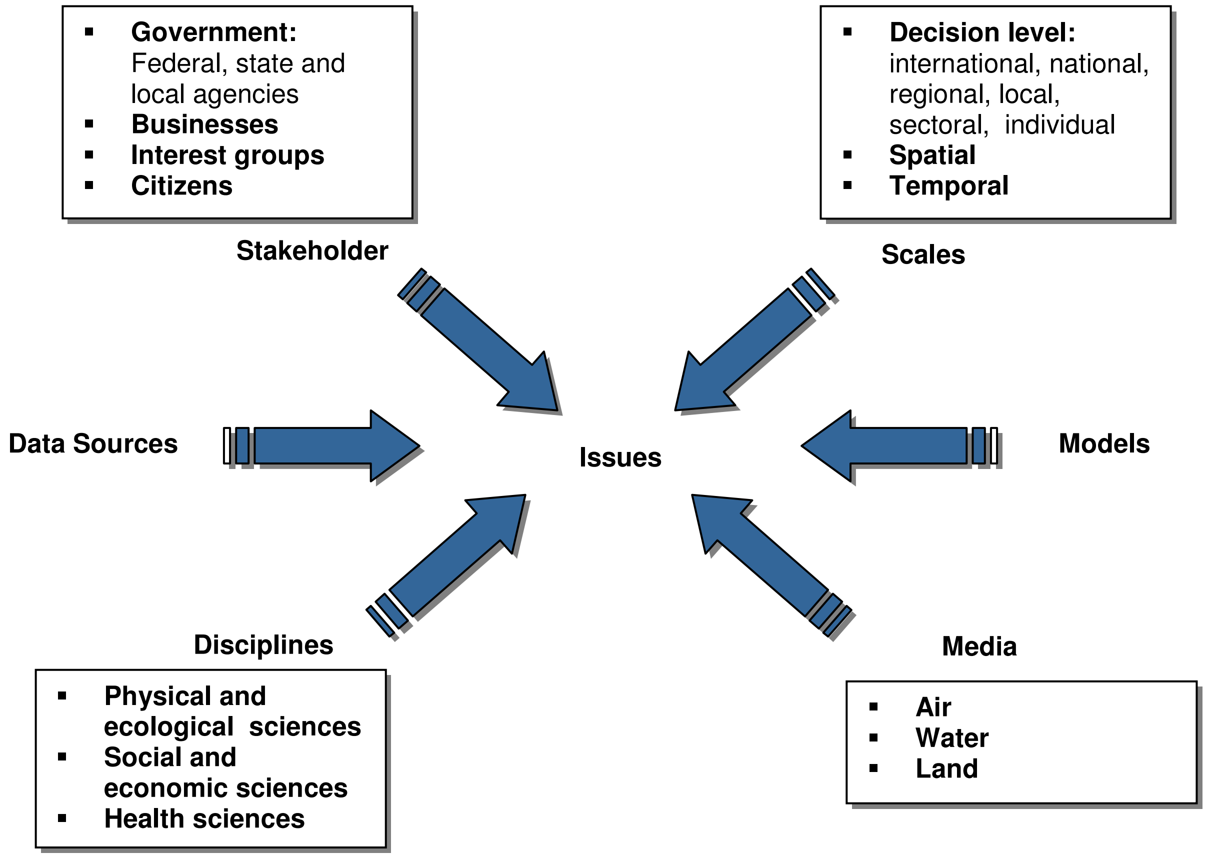

Figure 3: Issues of Scale and Dimensions of Integrated Modeling [17]

2.2 Applications of integrated modeling: For what purposes are/ should integrated modeling be used?

Integrated modeling is applicable to a wide spectrum of environmental assessment and management needs, including providing better conceptual understanding of the interconnectedness among the components of the environmental systems, as well as in the prospective and retrospective assessment of policies (See examples in Box 2.1 and section 2.1.1). The level of complexity with which the components are expressed in the modeling system should be determined as a function of: the requirements for accuracy in results; the available data and models; and the available resources (schedule, personnel and computational). Integrated modeling allows comparison among different policy options and scenarios by simulating the physical, ecological and social consequences of pre-defined policies (policy evaluation

[17] Adapted from: Parker, P., Letcher, R., Jakeman, A., Beck, B., Harris, G., Argent, R., Hare, M., Voinov, A., Janssen, M., Sullivan, P., Scoccimarro, M., Friend, A., Sonnenshein, M., Barker, D., Matejicek, L., Odulaja, D., Deadman, P., Lim, K., Larocque, G., Tarikhi, P., Fletcher, C., Put, A., Maxwell, T., Charles, A., Breeze, H., Nakatani, N., Mudgal, S., Naito, W., Osidele, O., Eriksson, I., Kautsky, U., Kautsky, E., Naeslund, B., Kumblad, L., Park, R., Maltagliati, S., Girardin, P., Rizzoli, A., Mauriello, D. Hoch, R., Pelletier, D., Reilly, J., Olafsdottir, R., Bin, S. (2002) 'Progress in Integrated Assessment and Modelling' Environmental Modelling and Software 17(3), 209-217

models); helps to identify "welfare maximizing policies" based on cost-benefit analyses (policy optimization models) or determines the set of policy options and paths that are compatible with defined limits (policy guidance models).[18] Integrated models have also been described as powerful and indispensable tools for policy integration. The policy-relevant roles of integrated models include[19]:

- Providing a solid knowledge base for decisions that affect different sectors by assimilating fragmented knowledge from different sources;
- Forming the basis for outlining scenarios to help select alternative policies to deal with complex issues;
- Supporting the discourse between stakeholders by building scenarios that can make inter-relations of complex systems intelligible.

Investing in the development of an integrated modeling infrastructure will result in substantial returns, with efficiencies that benefit both the modeling and the decision making communities. The following examples of circumstances requiring integrated modeling approaches were presented at the workshop. These are only illustrative; the full range of applications is limited only by the imagination of stakeholders who formulate problem statements and design solutions. Integrated modeling is desirable to:

1. Assess multiple media (e.g. to capture interactions among the atmosphere, hydrosphere, and land), multiple sources (e.g. multiple anthropogenic influences), multiple stressors (e.g. multiple pollutants), multiple pathways, and multiple receptors;
2. Address multidisciplinary questions, or those in which social, political, and economic factors might substantially influence decision-making;
3. Analyze systems where processes and systems are significantly linked through two-way (or greater) coupling and feedback;
4. Clarify information for decision makers without resulting in an unacceptably high level of uncertainty;
5. Link source information (emissions) to ambient concentrations (whether in air, water, or soil) and, finally, to human health or ecological effects;
6. Conduct cost-benefit analysis and valuation of ecosystem services;
7. Weigh many alternative regulatory or management scenarios;
8. Develop adaptive management strategies;
9. Identify potential sources of observed environmental degradation.

[18] Jaeger, C., Leinbach, M., Carraro, C., Hasselmann, K., Hourcade, J.C., Keeler, A. and Klein, R (2002) Integrated Assessment Modeling: Modules for Cooperation, Foundazione Eni Enrico Mattei Working Paper 53-2002
[19] Arena (2004) Understanding Sustainable Development: Models, Data and Policy. Final Workshop Report. Seggau, 17-19 October 2004.

Box 2.1 Applications of an Integrated Environmental Modeling and Management Approach

Retrospective Analysis: MTBE, the paradox of unintended consequences

Methyl tertiary butyl ether (MTBE) was widely used to meet the requirements of the Clean Air Act Amendments of 1990, which stipulated that to reduce harmful vehicle emissions, areas with severe problems in attaining the National Ambient Air Quality Standard (NAAQS) for ozone use Reformulated Gasoline (RFG) containing 2% oxygen by weight. While the use of MTBE as a fuel additive in gasoline has helped to reduce harmful air emissions, it has also caused widespread and serious contamination of the nation's drinking water supplies. Unlike other components of gasoline, MTBE dissolves and spreads readily in the groundwater underlying a spill site, resists biodegradation, and is difficult and costly to remove from groundwater. Low levels of MTBE can render drinking water supplies unpotable due to its offensive taste and odor. At higher levels, it may also pose a risk to human health[20]. Evaluation of the toxicity of MTBE had been initiated by EPA in 1987 under the Toxic Substances Control Act (TSCA). Studies that focused on inhalation as the pathway of human exposure were used by EPA to develop the inhalation reference concentration. By comparing this reference concentration with the "worst-case" chronic inhalation exposure scenarios, it was determined that it would be unlikely that the general population would be at appreciable risk of non-cancer health effects from MTBE inhalation[21]. While inhalation of MTBE in high concentrations has been shown to cause cancer in laboratory animals, the Agency concluded in 1997 that there is little likelihood that MTBE in drinking water would cause adverse health effects at levels that cause taste and odor problems. There is still much uncertainty about the extent of the health risks associated with chronic, low-level exposures to MTBE in drinking water.[22] As a result of the problems associated with the potential release of MTBE into the environment, EPA has determined that a comprehensive approach to such risk must include consideration of either reducing or eliminating the use of MTBE as a gasoline additive. This case illustrates the importance of obtaining a comprehensive understanding of the many risks and benefits associated with a substance throughout its life-cycle, including the potential multi-media, multi-pathway cumulative exposures.

Prospective Analysis: Developing a Biofuels Strategy

Integrated models would serve as an important component of the scientific analysis to inform the development of policies related to biofuels. In response to rapid technology development in the area of biofuels, EPA is launching an agency-wide effort to develop an integrated, multi-media biofuels strategy[23]. The National Advisory Council for Environmental Policy and Technology (NACEPT) advised the EPA to play a broader role that goes beyond its current legislative mandates under the Clean Air Act. They called for EPA to be a "critical agent for ensuring that biofuel development avoids environmental pitfalls and stays on the path of sustainable success", and to cooperate with other federal agencies to answer questions related to the multi-media impacts of the cultivation, processing, and distribution of biofuels[24]. NACEPT also recommended a new strategic framework for organizing EPA and interagency biofuels efforts, one that adopts a systems approach to the biofuels supply chain and urged EPA to adopt

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[20] Methyl Tertiary Butyl Ether (MTBE): Advance Notice of Intent to Initiate Rulemaking Under the Toxic Substances Control Act to Eliminate or Limit the Use of MTBE as a Fuel Additive in Gasoline; Advance Notice of Proposed Rulemaking, Federal Register, Vol 65 No 58, p 16093-16109, 20 Mar 2000

[21] Davis, J.M and Farland, W.H. (2001) The Paradoxes of MTBE, Toxicological Sciences, 61, 211-217

[22] Contaminant Focus: MTBE, The Hazardous Waste Clean-Up Information (CLU-IN) Web Site, http://www.clu-in.org/sec/Methyl_Tertiary_Butyl_Ether_(MTBE)/cat/Overview/, accessed July 27, 2007

[23] EPA Administrator Letter to NACEPT re: Biofuels, September 26, 2007

[24] NACEPT Letter to EPA Administrator, NACEPT's Initial Thoughts on EPA's Role in Biofuels, February 20, 2007

such a framework "so that all the programs and media within EPA can envision, analyze and take steps to assume their proper role in the overall biofuels program"[25].

A number of EPA activities are underway to address different aspects of biofuels development. For example, ORD's Ecological Research Program is developing a proposal to study the effect of biofuels production and use on ecosystem services in the Midwestern US. This Future Midwestern Landscapes study will examine projected landscape changes and consequent changes in ecosystem services resulting from the implementation of federal, state and local policies to encourage biofuels production. Increased biofuels production goals have been proposed as a policy to simultaneously address challenges related to growing energy needs and energy security, as well as increasing concern over greenhouse gas emissions from fossil fuels. While the potential of biofuels to address these challenges is acknowledged, many concerns have been raised about the short and long term impacts of biofuels production and use on ecosystems and human welfare. The proposed study will construct and analyze a set of alternative future scenarios of feedstock production, processing and biofuels use that are relevant to stakeholders. The construction of the scenarios will involve the use of an agricultural model, energy sector model and models to assign land uses and map baseline and changes in wetlands. Models will also be used to quantify and value ecosystems services associated with changes in carbon balance, soil productivity, water quantity and quality, wildlife habitat and air quality. Cost-benefit and cost-effectiveness analysis tools will also be developed to allow decision makers to evaluate different scenarios in terms of criteria such as changes in pollutant levels, economic concerns, etc.[26]

Identifying Policy Options: Developing a Regional Integrated Energy-Environment Analytical Framework

There is great need for economic, energy and environmental information to support sound energy and air quality planning at the state and regional level. This information is required to assist decision-makers in understanding the energy, economic, and environmental challenges presented by multi-pollutant management options and regional policy commitments. ORD's NRMRL (National Risk Management Research Lab) has been supporting the development of an integrated analytical modeling framework for the Northeast States by the Northeast States for Coordinated Air Use Management (NESCAUM). This analytical framework (Figure 4) includes MARKet ALlocation technology database and model (NE-MARKAL), the REMSAD and CMAQ regional air quality models and the BenMAP and COBRA health benefits assessment tools. This analytical framework is being developed to support the New England Governors and Eastern Canadian Premiers (NEG/ECP) climate action planning, as well as other pressing regional issues (e.g., achieving and sustaining National Ambient Air Quality Standards (NAAQS)). MARKAL provides a framework for exploring and evaluating alternative futures, and the role of various technology and policy options. The MARKAL model assists in identifying a least cost set of technologies to satisfy end-use energy service demands and policies specified by the user. It also quantifies the sources of emissions from the associated energy service system technologies and system-wide costs of energy and environmental policies.

[25] NACEPT Letter to EPA Administrator, NACEPT's Initial Thoughts on EPA's Role in Biofuels, July 13, 2007
[26] ORD (2007) The Future Midwestern Landscapes Study: A proposed evaluation by EPA's Ecological Research Program of Biofuels, Future Landscapes and Ecosystem Services in the Midwestern United States, July 19, 2007 draft

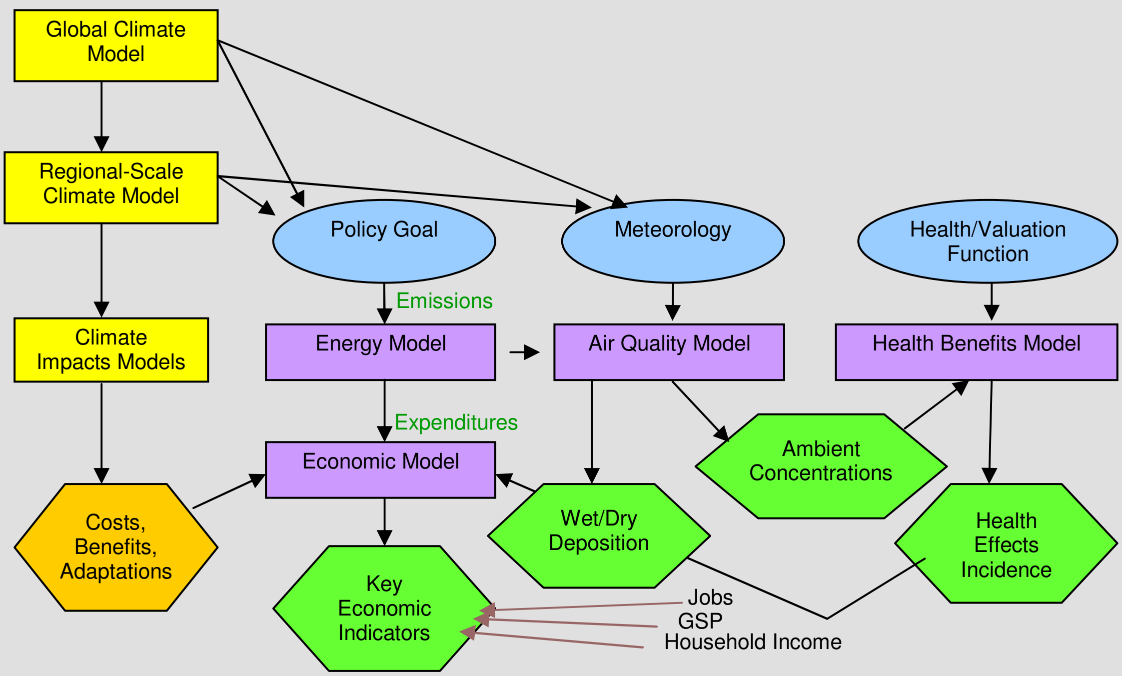

Figure 4: Integrated Regional Policy Analysis Framework[27]

Reactive Nitrogen: Complex environmental, human health and economic issues

Although nitrogen is an essential element, when present in excess, nitrogen compounds play a role in numerous negative environmental and human health effects. Reactive nitrogen (N_r) includes all biologically, chemically and radioactively active nitrogen compounds in the atmosphere and biosphere. It includes forms of nitrogen such as ammonia (NH_3) and ammonium (NH_4^+), nitric oxide (NO), nitrogen dioxide (NO_2), nitric acid (HNO_3), nitrous oxide (N_2O) and nitrate (NO_3^-) and organic compounds such as urea, amines, proteins and nucleic acids[28]. As a result of their high mobility and solubility, excessive amounts of reactive nitrogen compounds can quickly produce a series of impacts across air, soil and water (Figure 5).

Application of synthetic fertilizers in agricultural production is a major source of N_r, as is the combustion of fossil fuels for energy production and transport. While fertilizer application is important for increasing crop production to sustain human populations around the world, it also increases releases of N_r into groundwater, rivers and estuaries through agricultural runoff thereby promoting eutrophication. Emission of nitrogen oxides (NO_X) as a result of fossil fuel combustion contributes to higher levels of ozone in the lower atmosphere, causing respiratory ailments and damaging vegetation. Atmospheric deposition of N_r contributes to acidification of soils and water bodies, corrosion of structures and ecosystem imbalances. Denitrification of N_r produces molecular nitrogen as well as nitrous oxide that contributes to both the greenhouse effect and to stratospheric ozone depletion.

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[27] Northeast States for Coordinated Air Use Management (NESCAUM) http://www.nescaum.org/focus-areas/science-and-technology/integrated-analytical-framework
[28] UNEP and WHRC (2007) Reactive Nitrogen in the Environment: Too Much or Too Little of a Good Thing. United Nations Environment Programme, Paris

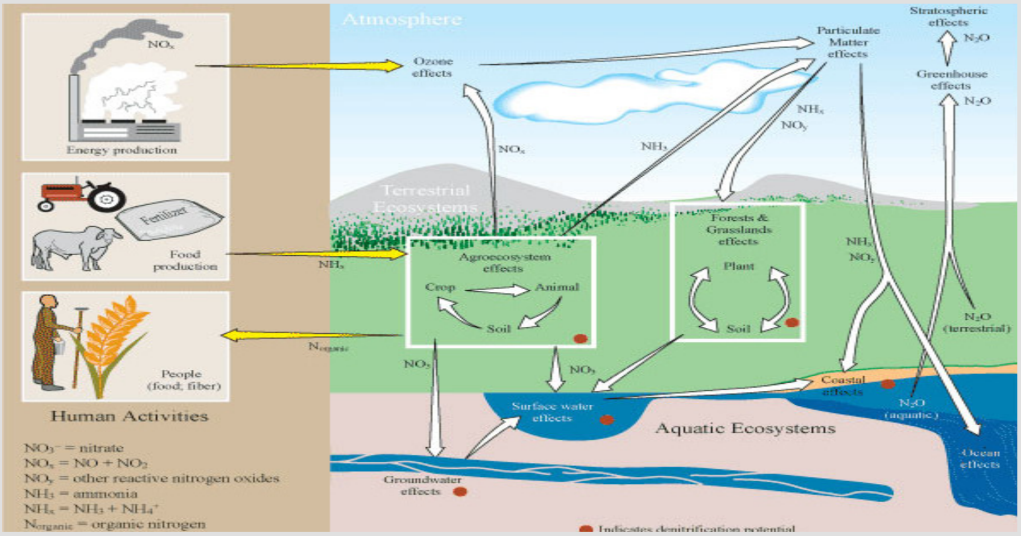

Figure 5: The Nitrogen Cascade[29]

As a result of its complex multi-media impacts, it is important that at a policy level reactive nitrogen-related problems are addressed from a systems perspective and integrated across environmental media[30]. Integrated models that deal with the important nitrogen forms, sources, and pathways are thus important to develop a comprehensive and coherent understanding of the issue and help to develop effective nitrogen management strategies[31].

A number of activities have been undertaken or are planned at EPA to address the complex issues surrounding reactive nitrogen. The ORD National Exposure Research Lab (NERL) has developed a project to identify and evaluate the uncertainties in nitrogen modeling that present the greatest barriers to the development of effective multimedia management strategies, in order to help prioritize EPA research efforts. The EPA has also requested that the Science Advisory Board conduct a study on how EPA can better develop strategies to reduce reactive nitrogen in the environment. The SAB study will assess the degree of integration among the current EPA programs, make recommendations for a more integrated research program on N_r, and identify opportunities for a more integrated approach to nitrogen management. The pollutant-specific component of ORD's Ecological Research Program (ERP) will on N_r. The ERP will develop, publish, and review a research strategy for Multimedia Reactive Nitrogen within the context of the ecological services framework of the Ecological Multi-Year Plan. It will also develop the conceptual framework for a multi-media decision-support tool for Nr measurement based on the optimization of ecological services affected by changes in forms and flows of Nr from anthropogenic sources at regional and watershed scales. The goal is that by 2013 half of EPA Regional Offices and all coastal states, including those on the Great Lakes, will be using guidance and decision-support tools developed by ORD and its partners to meet Clean Water and Clean Air for N_r[32].

[29] Gallowy, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B. and Cosby, B.J. (2003) The Nitrogen Cascade, BioScience 53: 341-356
[30] Sliggers, J. (2004) The need for more integrated policy for air quality, acidification and climate change: reactive nitrogen links them all. Environmental Science and Policy, 7: 47-58
[31] Dennis, R. (2004) Evaluation of Significant Uncertainties in Modeling Nitrogen Cycling to Support Multimedia Management Strategies, EPA NERL Research Abstracts website: http://www.epa.gov/nerl/research/2004/g4-7.html
[32] ORD (2007) Ecological Research Program Strategic Directions 2008-2014, Preliminary Draft, April 2007

2.3 Examples of Integrated Modeling Activities

The state of the art and practice in integrated modeling and assessment is in its adolescence, that is, it is well beyond its infancy but not fully matured. The need for integrated modeling for environmental decision-making is appreciated, and is being applied throughout the world community of environmental scientists and decision-makers. However, for the most part, the concept is applied in a widely varying manner using widely varying technological approaches. Current applications clearly demonstrate the utility and value associated with integrated modeling. Examples of existing and developing integrated modeling programs and projects both from outside and within the Agency are presented in the Appendix.

CHAPTER 3: CURRENT CHALLENGES

Integrated modeling provides a means for capturing and synthesizing the diverse science and data needed to inform environmental decision-making. Currently, the concepts related to integrated modeling are increasingly appreciated and are being applied by a growing majority of the science-based environmental community. Evidence of this growing understanding was clearly on display at a recent workshop on integrated modeling. Examples of integrated modeling projects from all sectors of the Agency were presented and discussed. Managers confirmed the critical role of integrated modeling in supporting the decision process, and strongly encouraged further progress. Modelers and analysts discussed a wide range of issues and implications related to the practice of integrated modeling. While these signs of progress are unmistakable, necessary, and significant, they also indicate, by their relatively fragmented and ad hoc nature, that the movement toward more wide use of integrated modeling remains faced with significant challenges that hamper the realization of its true value.

The following discussion highlights key issues that have surfaced with respect to the science, information technology, and organizational issues involved in advancing the state of the art and application of integrated modeling and environmental systems analysis.

3.1 Science Challenges

Among the important science issues that surfaced in the context of integrated modeling are: ***design of the integrated analytical framework, model evaluation and uncertainty analysis, and education and knowledge management***.

Integrated Analytical Frameworks

An integrated analytical framework conceptually provides a set of consistent and compatible science-based components (data and models) and describes how these components are to be organized/ linked and employed to address a specific problem in a coherent manner. For modern integrated modeling, the problem statement (a description of the nature and scope of a specific problem that needs to be addressed) is highly important. Matching integrated modeling solutions to problem statements will require clear communication among all stakeholders in both the formulation of the problem statement and the development of an integrated science-based solution.

Another important aspect of integrated analytical framework design is the selection of internally consistent and compatible science components. Multimedia modeling and multi-disciplinary modeling dealing with multiple spatial and temporal scales can be complex. To achieve internal consistency in the integrated analytical framework, it is crucial that in addition to dealing with spatial and temporal differences that the methodological and modeling techniques and differing assumptions are also captured and reconciled. For example, numerical models of the atmosphere and surface water typically operate on very different time steps and grid cell resolutions. When sharing data between these models these scaling issues must be addressed such that errors due to scale dependent transfers are minimized. Temporal scale is also very important in economic analyses that ascribe monetary and non-monetary costs and benefits. Efficient transfers and integration across the boundaries between different disciplines or knowledge domains is a critical science challenge.

Another important model component linkage issue is model dynamics, i.e., bi-directional coupling (feedback) versus uni-directional linking (feed-forward). Bi-directional integrated models are much more challenging—and require greater computing resources—than unidirectional integrated models. Examples of problems requiring feedback modeling systems include simulation of contaminant movement between the atmosphere and land surface and between groundwater and surface water. Without including these dynamic feedback interactions in these simulations achieving system wide mass balance is very difficult. Depending on the problem statement this may or may not be a critical issue. Where the problem does require the consideration of feedback the challenge will be to develop a sound science approach that can be implemented within the computational constraints imposed by the available hardware and software.

Model Evaluation and Uncertainty Analysis

Validation of complex, integrated modeling systems is particularly challenging. Validation, in this context, refers to corroboration of the modeling system's ability to simulate the relevant processes. Validation typically includes applying the model to generate estimates of conditions that have been observed. Validation is the principal means by which to establish a model's ability to provide credible and defensible results. Validation becomes more difficult with increasing complexity of the integrated system. Integrated observational datasets that can support complex modeling designs are scarce. In the future, evaluating a modeling systems predictive ability will require new methods.

Related to validation is the need for comprehensive and quantitative methods for assessing uncertainties associated with modeling and model results. Uncertainties in the scientific sense are a component of all aspects of the modeling process. Uncertainties that affect model quality include aleatory uncertainty (due to the inherent stochastic nature of the world), uncertainty in the underlying science and algorithms of a model (model structure uncertainty), data uncertainty, and uncertainty regarding the appropriate application of a model (application niche uncertainty). Uncertainty analysis provides stakeholders a structured means by which to assess the strengths and limitations of model predictions. Again, integrated modeling presents a challenge to the science community to develop methods that provide a comprehensive view of the uncertainties in a format that is comprehensible and provides utility to decision makers[33].

Education and Multidisciplinary Knowledge

Another challenging aspect of integrated modeling is education. As modeling systems become more varied and sophisticated, more effort must be organized around educating stakeholders. This education is essential and must reflect an appreciation of the fact that not all stakeholders are scientists. However, all stakeholders must be comfortable with the information that models provide. It is imperative that modelers understand the requirements and perspectives of different stakeholders and present modeling information in a clear and understandable manner.

The expertise of individual modelers is also of relevance. For example, a modeler may have complete knowledge of a specific model or general knowledge of a number of models but rarely will he/ she have both kinds of knowledge. Therefore, two types of modelers are needed—specialists in individual models and model integration specialists. Disciplinary differences pose other problems. Integrated modeling requires interdisciplinary knowledge and collaboration; however, differences in scientific and program cultures and training present a challenge. Improved understanding and collaboration among modelers is required to successfully integrate disciplines within a model.

3.2 Information Technology Challenges

Information technology (IT) plays an interestingly critical role in the advancement of integrated modeling. While science must form the basis for integrated designs, IT provides the mechanistic means by which to implement integrated solutions. The relationship between IT and science, like the relationship between modeler and decision-maker, is closely linked. That is, each is essential to the other for success to occur. Among the known and important issues facing integrating modeling from an IT perspective are: ***achieving interoperability; automated data access, retrieval, and processing; and the development of decision support interfaces***.

Achieving Interoperability

The domain of components for integrated modeling systems is essentially limitless. Sources of data available from national and international monitoring programs, including those provided by satellites, continue to increase at a prolific rate. Modeling components that simulate physical, chemical, and biological processes occurring throughout the stressor – response continuum are under constant development (Figure 6). These latter models are based on specific assumptions and are intended for use

[33] Beck, M.B., Ravetz, J.R., Mulkey, L.A., Barnwell, T.O.. (1997). On the Problem of Model Validation for Predictive Exposure Assessments. Stochastic Hydrology and Hydraulics, 11:229-254

within defined application boundaries. Models and data are combined and applied in numerous ways to provide for specific assessments. Modeling results are processed and presented to stakeholders in diverse ways. Facilitating the selection and processing of this wide and deep assortment of components for the purpose of constructing modeling systems that efficiently respond to a similarly wide range of problem statements in a timely manner is indeed challenging.

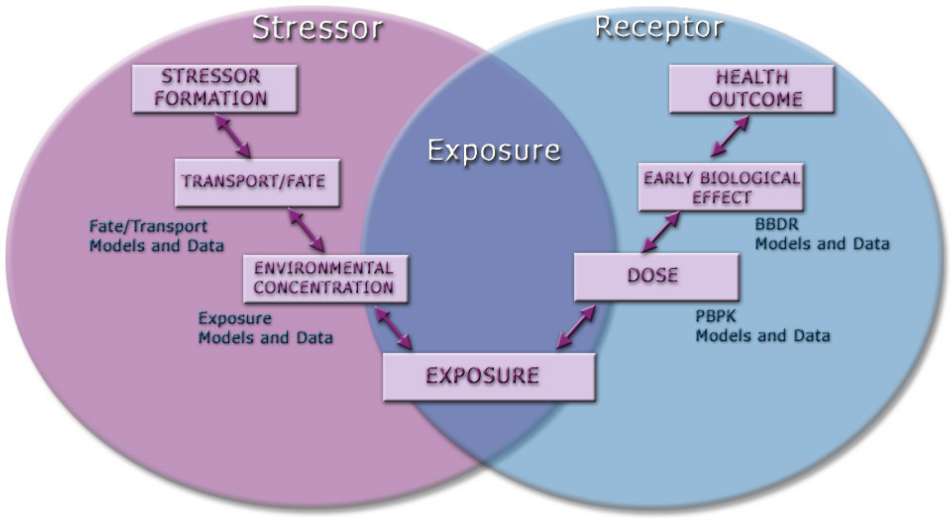

Figure 6: Stressor-Response Continuum

Integrated modeling requires that components "interoperate", that is, as discussed earlier, function together with coherence, transparency, reproducibility and characterized uncertainty and quality assurance. Barriers to interoperability remain a major constraint to accessing usable modeling resources. Facilitating interoperability among models requires sophisticated supporting software infrastructures, often referred to as modeling frameworks[34]. A modeling framework provides a standards-based software architecture that performs the support functions necessary to both define and operate a modeling system (i.e. a collection of components and related interrelationships). In defining a modeling system, a framework provides protocols and utilities to allow a user to inform the infrastructure concerning component attributes, most importantly information about data inputs/ outputs and rules for execution. Operationally, a framework manages the rules-based execution schemes for components and the information/ data flow through the system. Frameworks can also include support software to facilitate data visualization and analysis tasks and the packaging of end-user applications that can be effectively used for decision-making[35]. At the core of all frameworks are standards for the transfer and exchange of

[34] Purwasih, W. and Nakamori, Y (2004) Structured Modeling Technology: A modeling environment for integrated environmental assessment, in Pahl-Wostl, C., Schmidt, S., Rizzoli, A.E. and Jakeman, A.J. (eds), *Complexity and Integrated Resources Management, Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society*, iEMSs: Manno, Switzerland, 2004. ISBN 88-900787-1-5.
[35] Rizzoli, A., Lepori, C., Mastropietro, R. and Sommaruga, L. (2005) Developing an Environmental Modelling Framework for Integrated Assessment of EU Agricultural Policies. ERCIM News No. 61, April 2005, European Research Consortium for Informatics and Mathematics

information and data through the system. These standards represent the means by which disparate modeling components communicate. Just as the computer industry has established standards to allow various hardware components manufactured by different companies to interoperate a modeling framework includes software standards to facilitate the interoperation of modeling components developed by different individuals and groups.

While the development of frameworks and associated standards is necessary for the future of environmental modeling, a problem exists with the current approach. The first generation of modeling frameworks was developed according to "local" standards, that is, for example, each framework development project establishes its own set of data exchange protocols. Thus, the standards are not industry-wide and this results in two significant limitations. First, science components are not efficiently reusable and interoperable across frameworks. This is most important because of the need to utilize science models across disciplines and the desire to conduct research related to comparing the science across models. Secondly, the vast majority of software written for frameworks performs functions that are common to all frameworks, e.g. data exchange, model execution, data visualization, etc. These support functions often end up being custom designed and implemented for each framework system, thus, essentially wasting resources on redundant tasks. The primary challenge facing integrated modeling from an IT perspective is the establishment of community-based standards that will facilitate the reuse and interoperability of components.

Metadata is another important aspect of information standards. Metadata is information that accompanies a modeling component. This additional information describes attributes of the target data, for example, the name and contact information of the original developer of the data. As more components become available (i.e. data and models) it will be of great benefit to publish them along with their metadata to facilitate a users understanding of their genesis, pedigree, application history, etc. The development of ontologies potentially plays a role in facilitating the interoperability among data sources, including models. Ontology development exploits relationships among data to search for and retrieve information, in contrast to the methods used by text-based data search engines. Although potentially significant, the ontology development process is labor-intensive and can require retooling for each type of application. Considerable efforts are needed in this area, particularly in the daunting task of reconciling disparate sectors and groups. Possible considerations for EPA include: (1) controlled vocabularies; (2) ontologies that capture functionalities between and within models and among data sources; and (3) self-describing models.

<u>Data Issues</u>

Automated access, retrieval, and processing of data from a myriad of sources is important for successful implementation of integrated modeling (see Box 4.1). While the database world is increasingly providing standardized means for accessing and retrieving data, issues related to data quality, pedigree and processing (i.e., preparing data for use in models) remain to be addressed. Modeling systems must integrate data from a myriad of sources, each with its own approach to data quality. It is necessary to understand this variability and specifically account for its impact, for example, on uncertainty. Pedigree, i.e., the history of a data set, is important and will require automated means to establish, document, and maintain it. Processing "raw" data into the form required for input to models can require sophisticated statistical analysis and modeling in its own right. Providing automated tools and methods to execute and document this processing is important. The degree to which these "data related" needs are met using community based software development standards will be important in both conserving resources and facilitating state of the science solutions to regulatory problems.

Box 3.1 Critical issues for the use of data in modelling and assessment studies[36]

crucial that coherent and detailed metadata are elaborated.

2. Decisions on how to organize the dataset dates back as far as to the late 1960s. These datasets often lack crucial information that is needed to assess current policies as aims and objectives of the policies have changed over time. This means that information on some issues has to be provided from other sources than the consistent databases. To remedy this it is necessary to develop methods, such as typologies, to link data from different data sources.
3. Databases are organized at different spatial levels ranging from administrative regions to very detail grid systems with a variety of purpose specific regions in between. This means that the different databases cannot easily be linked and that methods need to be developed to integrate the data spatially.

Development of decision support interfaces

As regulatory problem statements continue to grow in complexity the number and complexity of possible solutions also grows. Decision support systems represent the means by which to express the essence of the integrated science for the purpose of informing decisions. Decision support systems are designed to answer the myriad of "what if" questions related to decision options. These systems must achieve this end with clarity, efficiency, and with definitive statements regarding the limits of interpretation and uncertainties related to/ derived from the science based information. Developing effective decision support systems to complement integrated science and modeling will require the specific attention and collaboration among all stakeholders.

[36] Ewert. F.A, van Ittersum, M.K., Bezlepkina, I., Oude Lansink, A.G.J.M, Brouwer, F.M. et al. (2005) Development of a conceptual framework for integrated analysis and assessment of agricultural systems in SEAMLESS-IF, SEAMLESS Report No.1, SEAMLESS integrated project, EU 6th Framework Programme

3.3 Organizational and Institutional Challenges

The importance of science and technology in the context of integrated modeling is intuitively clear. What has not been as clear is the importance of organizational integration (both within EPA and among EPA and other organizations). Integrated science and technology are only possible when people come together and commit to sharing and implementing ideas. Organizations can be the greatest facilitator of these interactions or their greatest barrier. The willingness and ability of EPA offices and staff to undertake integration for both modeling and decision-making can be impeded by a number of human, organizational and institutional factors. These include limited time and resources and poor communication and collaboration across disciplines and EPA programs. Poor communication is also a barrier to the re-use of models developed by other groups in the Agency, resulting in a tendency to rely on existing models or duplication of efforts.

Principal among these factors is institutional and organizational stove-piping, a systemic challenge that hinders effective and meaningful inter-office collaboration. The EPA institutional and statutory structure does not greatly facilitate consideration of cross-media interactions. Policies often require the Agency to address a certain problem (e.g., air quality or water quality) individually, via multiple, stove-piped statutes, without allowing for adequate assessment of complex multimedia impacts of the proposed solutions or actions. These statutes include the Clean Air Act (CAA); Clean Water Act (CWA); the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); the Resource Conservation and Recovery Act (RCRA); and the Toxic Substances Control Act (TSCA). Poor intra-Agency communication hinders cross-fertilization of ideas and true interdisciplinary, inter-office collaboration within EPA.

In addition to these institutional issues, EPA is faced with a major human capacity challenge. Within the next 5 years, approximately 45% of EPA's workforce will be eligible for retirement. This retirement wave is expected to disproportionally result in the loss of modeling expertise within the Agency, especially at the regional level.

CHAPTER 4: IMPLEMENTING THE STRATEGIC VISION

4.1 Key Considerations

Action to implement the strategic vision for integrated modeling outlined in section 1.1 should be informed by a number of key considerations, as identified in the discussions and findings of the January 2007 workshop.

- **Integrated modeling is a broad term** that applies to a continuum of models ranging from simple to complex, thus the concept of "one size fits all" or "one solution fits all problems" does not apply.
- **Integrated modeling does not necessarily lead to integrated decision making**. If integrated decision-making is desired, a management structure or agreement must be in place to encourage that to occur.
- **Model users and those responsible for making decisions should be included in all steps of a modeling solution.** Discussions between scientists, modelers, stakeholders and decision makers are crucial for defining the environmental problem, the purpose of the modeling, and the desired outcomes. Once a modeling approach is chosen, ongoing discussions among interested parties are needed to ensure that modeling objectives, budget and timelines continue to be met or are appropriately adjusted.
- **Integrated modeling often requires collaborative efforts and outreach within and outside of EPA** to ensure that the appropriate level of expertise is available to address scientific, technical and managerial (i.e. policy and decision making) aspects of the modeling exercise.
- **Integrated modeling requires high-level agency support**, especially for problems that cross scientific disciplines or programs, or where more than one governmental agency has an interest. This support can result in actions that break down institutional barriers, and/or that provide incentives to encourage integration of modeling activities. Proceeding with integrated modeling projects incrementally on an ad hoc basis, as the Agency has done to date, is expected to yield progress, but a strategic organization-level solution would provide greater environmental benefits at reduced long-term costs.
- **Achieving integration goals requires investment.** There is considerable overhead involved in connecting the community and establishing the working conditions necessary to achieve integration across the science-based disciplines involved in environmental modeling. Because the result of this investment in community infrastructure is not immediately tangible, that is it does not target or solve a specific regulatory problem, it presents a unique challenge to managers and scientists to garner and apply resources.

4.2 Action Plan Goals

The Strategic Vision and Action Plan proposed in this white paper seek to provide a holistic response to the science, information technology and organizational challenges facing the coherent and consistent implementation of integrated modeling in EPA. While the set of proposals are illustrative, not exhaustive, they are designed to be mutually-reinforcing with the overarching goal to create an enabling environment that will:

- Promote better understanding of integrated modeling, its purpose, utility and applicability;
- Raise the profile of integrated modeling, and communicate its importance to Agency upper management;
- Develop infrastructures that enhance interoperability among information sources, including models and data;
- Implement mechanisms to enhance communication, coordination, collaboration and knowledge sharing among stakeholders (i.e., scientists, modelers, risk assessors, decision makers and affected stakeholders);
- Promote more consistent modeling and analysis across EPA offices;
- Foster an enhanced analytical ability to characterize, communicate and understand uncertainties associated with integrated modeling and the implications of these uncertainties for decision-making; and
- Enable more transparent decision-making supported by objective sound scientific analysis.

4.3 Action Plan

This action plan outlines requirements for establishing an organization-level solution to facilitate a concerted, systematic, and stable approach to the development and application of integrated modeling at EPA. The requirements are interdependent and form an integrated foundation for all Agency Programs. These areas and their interrelationships with each other and the existing statute driven architecture of the organization are shown in Figure 7. In the end, it is envisioned that the individual Agency Offices and Programs (shown as stovepipes in Figure 7) will contribute to and utilize a community center of knowledge and technology for integrated modeling (yellow box in Figure 7). Knowledge and technology will also flow to the community center from all sectors of the stakeholder community.

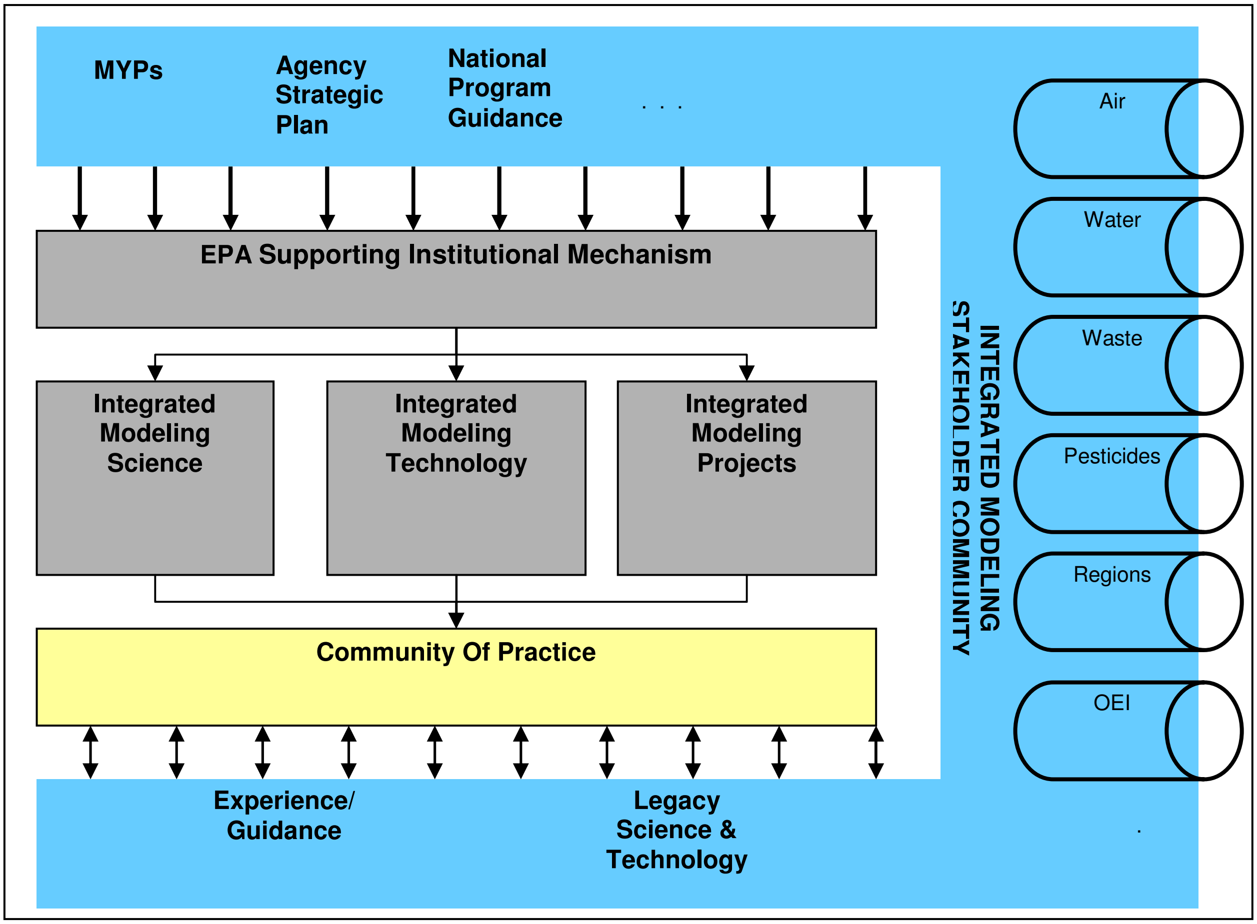

Figure 7: Integrated Modeling Action Plan

4.3.1 Requirement 1: An Integrated Modeling Supporting Institutional Mechanism

To focus Agency efforts with respect to integrated environmental modeling, an institutional mechanism is needed to catalyze, incentivize and support the collaborative process necessary to achieve integration by engaging multiple offices/regions in the development, documentation, testing and application of mutually needed modeling technologies. Furthermore, this organization would accelerate progress in overcoming institutional barriers to integrated modeling by proactively fostering improved coordination across offices, improved accessibility of information and knowledge and reduction of unnecessary duplication of effort. This organization would provide a deliberate and sustained mechanism to facilitate knowledge sharing and coordinate the initiation, operationalization and analysis of integrated modeling activities throughout EPA.

- ***Initiation:***
  - Provide a forum for coordination and leadership in the Agency to identify issues that would benefit from integrated modeling/ decision-making;

- Improve scoping to define relevant policy questions and direct integrated analyses to areas where they are appropriate and practical in terms of cost.
- Engage key individuals, groups, Offices and Programs in an effort to define and prioritize the integrated modeling technical activities to be undertaken.

- ***Operationalization:***
  - Determine and implement the appropriate organizational placement for work that has been identified as a priority. This could involve recruitment across the Agency to build and fund an action team that would be charged with a relatively short term goal to investigate, resolve and/ or apply key science-based technologies related to the development of identified, priority integrated modeling systems.
  - Maintain ongoing involvement in the conduct of the model development and application efforts to provide guidance, review and accountability oversight.
- ***Analysis:***
  - Provide a forum for discussions and review from among the Agency modeling community so that the common challenges met and lessons learned from experience are documented and widely-shared.
  - Archive the products of specific technical activities (development and applications) for access and use by the larger community.

At the heart of this vision is the belief that real cross-Agency collaboration is achievable. As stated previously, there are many natural barriers to establishing collaborative efforts (including differences in mandated time lines, organizational and philosophical separation among potential collaborators, the need for resource sharing, procedures for project decision-making, etc.). These barriers are best addressed during the planning process since it is significantly more difficult to remove them once individual efforts have begun. Thus, a major focus for this institutional mechanism would be to address these barriers using an upfront planning and negotiation process by establishing an environment where all contributors see a single goal, a single timeline, a unified source of funding, clear delineation of roles and where it is understood that individual success is dependent on group success.

The Council for Regulatory Environmental Modeling (CREM), based in the Office of the Science Advisor, might provide the permanent staff resources to support the planning and operation of this organization and its activities. The organization's charter, including details of its composition, governance structure and resource level, will have to be determined through Agency-wide discussions. We note again that it is vitally important that such an organization receives sustained, strong and meaningful support from senior Agency management.

Rather than establishing a stand-alone program for integrated modeling, it is important to develop a framework organization through which allied groups promoting a systems analysis approach can collaborate and coordinate their activities to ensure maximum effectiveness in helping EPA adopt a more integrated approach to environmental decision-making. Thus opportunities for partnering through this organization should be vigorously pursued with entities within and outside EPA to ensure development of critical resource mass and coherence in the way information developed is used.

4.3.2 Requirement 2: Dealing with Integrated Modeling Science Issues

Collaborative research and development activities are needed to advance the state of the science for integrated modeling. At present there are several issues that would benefit from a collaborative research and development effort, for example: 1) modeling of inter-media transfers of contaminants, 2) ecosystem services and related valuation methods, and 3) uncertainty analysis for highly integrated modeling systems. This is by no means an exhaustive list, but rather serves to describe the types and classes of science needs related to integrated modeling.

<u>Intermedia transfer of contaminants</u>

Integrated model simulation of the multimedia movement of contaminants in the environment is complicated by knowledge gaps related to the physical/ chemical processes controlling intermedia transfer, differences in spatial and temporal scales and the mathematical handling of feedback (i.e., the bi-directional vs. unidirectional flow of contaminants across media boundaries). Furthermore, the computational implications related to numerical solutions of the governing equations involved can be daunting. Technology alone cannot solve the intermedia fate and transport modeling issues, thus, research and development are necessary.

<u>Ecosystem services</u>

As a greater emphasis in Agency decision making is placed on ecological resources there is a growing consensus that it is necessary to establish the economic value of ecosystems, and in particular, the services ecosystems provide in the context of human welfare. Ecosystems provide a variety of services that can be grouped into several categories: supporting services (e.g., nutrient cycling), regulating services (e.g., flood regulation), provisioning services (e.g., food production) and cultural services (e.g., recreational). Elucidating the myriad of services related to each of the myriad of ecosystems, simulating the impacts on these services in response to the myriad of stressors that occur (e.g. pollutants, land-use change, global warming), and mapping the services to the myriad of constituents of human well being (e.g., security, health, basic material needs) and then establishing the economic values of the services is a rather large challenge. There are numerous organizations pursuing research in this area, including ORD, and it is necessary that this research is mined and organized such that useful guidance, tools and methods are made available to decision-makers.

Uncertainty Characterization and Analysis

As stated earlier, integrated models serve as a link between environmental decisions and the scientific evidence that provide empirical or theoretical support for these decisions. Administrative law and the principles of good governance dictate that if these models are to be legally defensible, they must be founded on the sound science of model development and evaluation. Stakeholders who are impacted by decisions that are based, even to some small degree, on integrated models, can exercise their statutory right to question the information used to construct those models. Model evaluation—problematic even for single models—becomes even more so when applied to multiple linked models. Integrated models can be useful probes into the nature of uncertainties and their significance in exploring the possible future implications of current decisions. However, systematic explorations of uncertainties and their implications using integrated assessment models present technical challenges[37]. Three areas of uncertainty analysis involving integrated models have been identified:

- Developing standard operating procedures and tools for assessing model uncertainty;
- Developing a standard approach for describing uncertainty to decision-makers;
- Assessing the impact of uncertainties on decision making risk.

To advance the state of the science of the domains of integrated model uncertainty analysis and model evaluation, some short-term opportunities are available:

- EPA recently issued a call for research into formal techniques to analyze uncertainty in the use of integrated models, both in terms of uncertainties within the models themselves as well as in uncertainties that arise during decision-making, when stakeholders discuss and evaluate the weight of scientific evidence embodied within the models.
- EPA is currently in conversation with other Federal agencies, including NASA and NSF, to issue a joint call for research in the use of integrated models, using the framework for the Global Earth Observation System of Systems. The GEOSS framework conceives of environmental models within a holistic decision support system (DSS), not only linking data, models, and decision-making into one seamless system, but also encouraging researchers to incorporate model documentation and uncertainty analyses into the DSS design.

4.3.3 Requirement 3: Dealing with Integrated Modeling Information Management and Technology Issues

As with the science issues, integrated modeling information management and technology (IMT) would benefit from greater leadership and coordination. The following are the key IMT needs:

- Review the current status and trends in information technology and research relevant to the design, and implementation of frameworks for model integration and distributed modeling.

[37] NRC (1999) Our Common Journey: A Transition Toward Sustainability, National Academies Press, Washington, D.C.

- Propose and support the development and adoption of standards for information flow related to integrated modeling. Standards would facilitate the reuse and interoperability of science based components without imposing restrictions of any kind on the conduct of the science itself.
- Facilitate the management of knowledge related to integrated modeling.

The development of the IMT infrastructure to support integrated modeling should be closely linked to the development and implementation of the EPA enterprise architecture (Figure 8), as well as build on information technology and management developments outside the Agency.

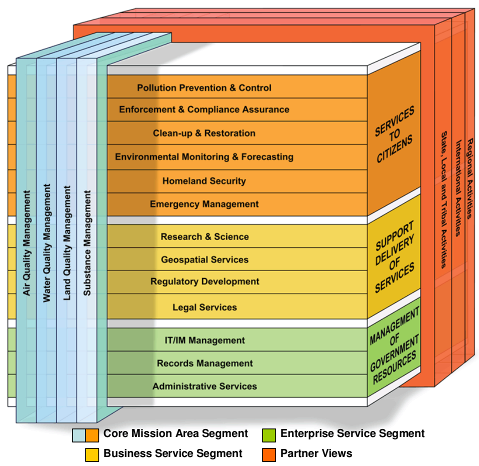

Figure 8: EPA's Enterprise Architecture Program

The EPA has recently signed an Implementing Arrangement with the European Commission to promote research and collaboration on environmental research and ecoinformatics. Included under this agreement is support for "cooperation for the development and common use of integrated environmental modeling frameworks or standards for enhanced model connectivity"[38]. Discussions with European counterparts have been initiated to develop collaborative projects under this agreement. To kick off the activities in this area, a workshop that focuses on the IT/IM aspects of integrated modeling within the wider scheme of information management in the Agency is proposed. This workshop would be jointly developed and hosted by the CREM, EPA GEO and OEI. The aim of the workshop would be to discuss and evaluate the different information technologies and approaches available to support improved interoperability for integrated modeling.

4.3.4 Requirement 4: Developing and Sharing Knowledge for Integrated Modeling

To reinforce the cross-Agency collaborative integrated modeling activities, a mechanism must be developed to facilitate the exchange of knowledge and experiences within the community of model

[38] Implementing Arrangement between the European Commission and the U.S. EPA to Promote Cooperation on Environmental Research and Ecoinformatics, http://www.epa.gov/international/regions/Europe/ec-epa-implementing-arrangement-revised.pdf

developers as well as among model developers and model users in EPA. The community of practice (CP) concept is a powerful tool for knowledge management, facilitating collaboration, training and fostering continuous improvement. An integrated environmental modeling CP would provide an effective mechanism for quick diffusion of innovation and rapid transfer of best practices among community members. Specifically, it would promote exchange of information, offer solutions for integrating models, provide expertise, assist in the characterization of models and serve as a resource to capture the community knowledge of models and frameworks. This type of resource would allow the Agency to efficiently build a more dynamic knowledge base. It would also facilitate communication and feedback from the model user community to assist model developers in improving the models and responding to user needs. The proposed online CP will utilize online collaboration tools, such as the EPA Environmental Science Connector (a centralized online resource for facilitating information sharing and collaboration across the Agency). Online discussions would be complemented by workshops organized to address specific scientific or technological cross-cutting issues. It is envisioned that the individual Agency Offices and Programs will contribute to and extensively utilize this community center of knowledge and technology for integrated modeling. Knowledge and technology will also flow to this community center from all sectors of the stakeholder community.

To help address succession planning challenges related to modeling expertise in the Agency, training activities could be developed through the CP. This new training program would not only focus on exposing staff to broad concepts of integrated modeling, but would also focus upon the maintenance of the modeling proficiency of scientific staff.

4.4 Application Areas and Demonstration Projects

It is anticipated that progress on the four “Requirement” areas just presented will be achieved, in part, through the development and implementation of demonstration projects that illustrate the utility of integrated modeling, analysis and management approaches. These projects would also be used to focus efforts to overcome some of the barriers and challenges to more consistent, cost efficient and systematic implementation of integrated modeling approaches and practices to inform Agency decision-making. Participants at the January 2007 workshop identified several challenging management areas that have immediate and meaningful utility to EPA’s mission and that would benefit from integration. Some project concepts are highlighted below. These serve as illustrative examples; further elucidation and prioritization of these and other projects would be achieved through discussions within the Agency.

4.4.1 Developing an integrated airshed and watershed model for the contiguous US

Goal: To support EPA's Total Maximum Daily Load (TMDL) implementation program by developing a multimedia model of the nation's airshed and watershed.

Outcome: Demonstration of the integration of air and water environmental management at all levels of government and decision-making from the national to the local scale, and the ability to provide least cost and most protective management approaches to be achieved through better coordination among federal, state, and local air and water management programs.

Potential Partners: ORD's National Exposure Research Lab Atmospheric Modeling Division, Office of Air, Office of Water and Regional Offices

Rationale and Approach:

The link between air emissions and water pollution is well known. This proposed activity would build on the experience gained in the Chesapeake Bay Program to develop an integrated airshed and watershed model for the contiguous US using the existing CMAQ model of the atmosphere and BASINS 4 for the watershed(s). The Chesapeake Bay Program model successfully linked the CMAQ and HSPF models on the regional scale, covering 6 states. The Chesapeake Bay Program model estimated that the primary nitrogen oxide (NOx) emissions airshed for the Bay is approximately 418,000 square miles; this is six and half times larger than the Chesapeake Bay watershed and includes emission sources from as far away as Canada (Figure 9) [39]. The product of the proposed project would be a calibrated model for the lower 48 States. Although work on linked airshed and watershed models is already taking place on an ad hoc basis in some regions, this proposed project would expand the scope of this work and go forward in an integrated, effective manner that fully harnesses economies of scale and would provides the efficiencies and consistencies of integrated environmental management to all regions rather than only a few.

[39] Chesapeake Bay Program Website: http://www.chesapeakebay.net/air_pollution.htm

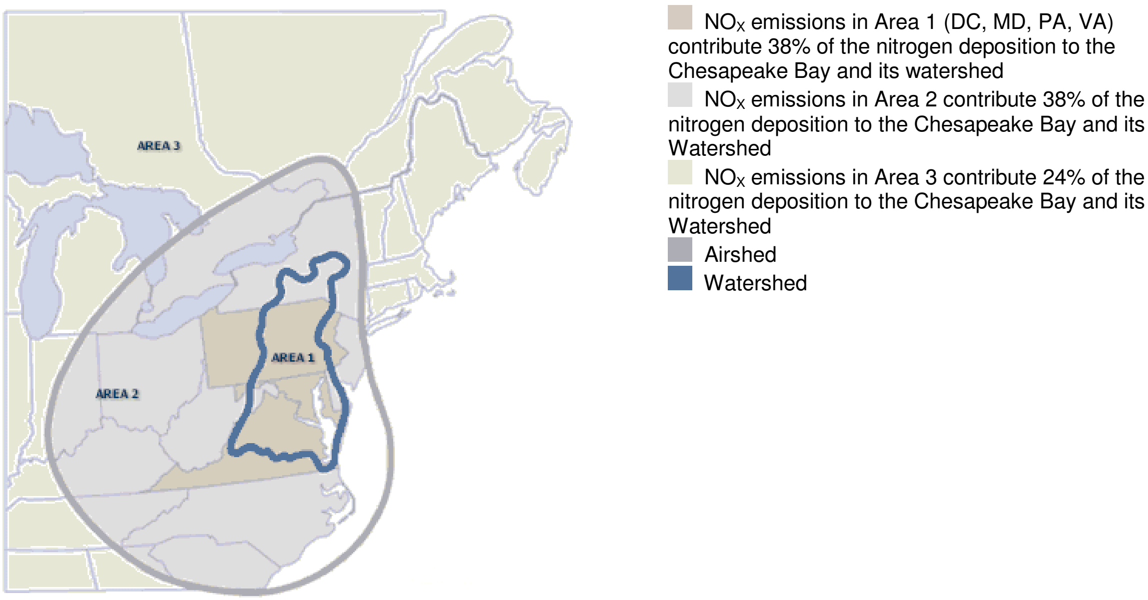

Figure 9: Areas of nitrogen oxide emissions that contribute to nitrogen deposition to the Chesapeake Bay and its watershed

An integrated model at the national scale would have the following advantages:

- Improved support of air quality programs, by including watershed and coastal water benefits of air management actions, would be provided, as well as the reciprocal improved support of water management efforts, particularly concerning cross-media pollutants such as mercury, nitrogen and toxics.
- Provide a nationwide, scientifically consistent and defensible modeling platform to test/demonstrate the utility of "Reconstructed Exposure" techniques for source identification (including chemical pollutants, land-use change/development, or climate change) and prioritization for address.
- Better and more complete assessment of the costs and benefits of environmental management by taking into account the full benefits of environmental quality in both media.
- Distributed decision-making at national, regional, state, and local scales would be encouraged, fostering more consistent integrated decision-making at the different jurisdictional levels.
- Support for TMDL development would be provided, at both the regional, large water body level and at the local scale that would help to reduce the backlog of 5,600 nutrient TMDLs due nationwide.
- Scientifically consistent support for estuarine and coastal water quality programs on the West, Gulf, and East coasts would be provided through support for estuarine/coastal models that can use the inputs from the airshed and imbedded watershed models for nutrients, metals and toxics.
- Using this nationwide integrated model, new modules could be developed for more uniform, consistent assessment of toxics, like PCBs and mercury.
- Support for improving monitoring programs provided by demonstrating the explanatory power of monitoring observations in combination with integrated model Simulated results, both prior to and

following key management or policy changes. Additional possible support includes analyses/optimization of monitoring site placement and network design based on criteria such as find the highest loads, use the least possible effective spatial coverage, or other metrics. Using the information available from existing monitoring networks, applying such an integrated model would expand our understanding of the monitoring observations within watershed contexts.

- Supports a refined, distributed examination of climate change impacts on water resources, water quality, and air quality with the Climate Assessment Tool (CAT) in BASINS. This application would be driven by files of downscaled input data of temperature and precipitation derived from global climate change models.

4.4.2 Informing land-use planning

Goal: To support the development and demonstration of a prototype integration of information sources and modeling tools for better land-use planning and environmental protection.

Outcome: Successful integration will augment existing land-use decision tools with scientifically defensible simulated information on related environmental and human health risks.

Potential Partners: EPA GEOSS and Region 5

Rationale and Approach:

Urban development, land-use planning and environmental management and protection are closely linked. One of the major challenges facing effective environmental management is the need to mitigate the impacts of urban development on environmental quality. An integrated environmental modeling approach would be useful by linking future urban development and growth scenarios with models forecasting resultant environmental quality. This approach would also be valuable for evaluating future local health and environmental impacts of climate change.

This project presents a rich opportunity to test the feasibility and limitations of model integration at watershed and other landscape scales (Figure 9) and the potential utility of "Reconstructed Exposure" techniques for key stressor source identification and prioritization for control/remediation. EPA's Advanced Monitoring Initiative (AMI) is supporting a demonstration study to integrate multiple AMI research projects across environmental media. The purpose of this demonstration is to advance the GEOSS "system of systems" concept regarding the interoperability of remotely-sensed data and environmental health assessment models that use these data. The targeted AMI projects are located in EPA Region 5, and involve urbanization of the landscape as a common denominator. Three of the projects are evaluating environmental health risks—bacterial exposure at beaches, Lyme disease risk in forested landscapes, and exposure to roadway emissions in Detroit. Three additional projects are developing landscape mapping tools that will digitize historic data from aerial photography, locate user-defined spatial features in pre-processed satellite imagery, and display projected emissions from alternative transportation scenarios. Each of these projects is applicable to at least one other project, with the expectation of added value. In addition, Region 5 is collaborating in the development of several decision-support tools that project runoff and other consequences of alternative land usage.

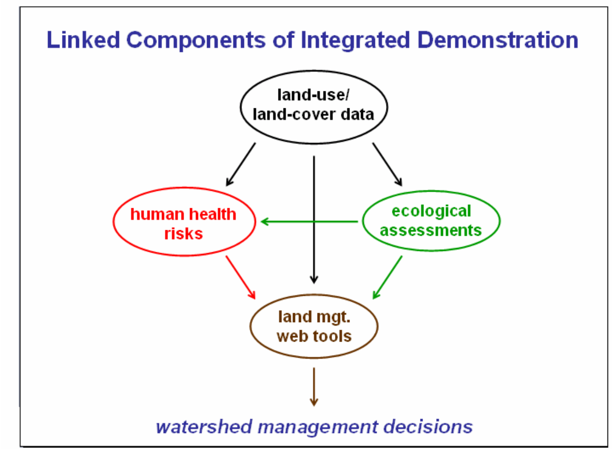

Figure 10: Integrated (Air-Water-Land-Biota) Decision Making for Healthy Communities and Ecosystems under EPA GEO AMI

4.4.3 Ecosystem services valuation

Goal: To develop an analytical framework for ecosystem services valuation.

Outcome: Improved prediction of environmental consequences of decisions.

Potential Partners: ORD's Ecological Research Program/ NESCS: Nonmarket Ecosystem Services Classification System

Rationale and Approach:

Ecosystem services have been defined as "components of nature, directly enjoyed, consumed, or used to yield human well-being"[40]. These include "provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on Earth"[41]. The lack of a standardized approach to measuring ecosystem services has hampered the development, acceptance and implementation of an environmental performance and accounting system. As part of the ORD Ecological Research Program, a conceptual framework termed the "Non-market Ecosystem

[40] Boyd, J. and Banzhaf, S. (2006) What are Ecosystem Services? The need for standardized environmental accounting units. Discussion Paper, RFF DP06-02, Resources for the Future, Washington, DC

[41] Millennium Ecosystem Assessment, UNEP (2005) Our Human Planet: Summary for Decision-Makers, Millennium Ecosystem Assessment.

Services Classification System" (NESCS) has been proposed. NESCS provides a standardized description of ecosystem services, the production of ecosystem services, the consumption (economic valuation) of ecosystem services, and how ecosystem services are related to each other and to market goods and services[42]. The NESCS thus both informs the development and relies on the use of integrated models addressing ecosystems, environmental quality conditions, administrative actions and economic analysis. The NESCS will be used to link the production of ecosystem services to the consumption of ecosystem services.

4.4.4 Sustainability Indicators

Goal: To support the development and use of meaningful ecosystem sustainability indicators that provide policy relevant information about the interactions between environmental, economic and social systems and also a comprehensive picture of the state of the environment and the pressures and trends thereon.

Outcome: Improved support for decision making processes by providing consistent, high quality indicators of ecosystem sustainability.

Potential Partners: Report on the Environment, Sustainability Outcomes and Indicators workgroup, Office of the Chief Financial Officer

Rationale and Approach:

Indicators are important components of the stream of information used to inform environmental decision-making at all levels. They provide representative, concise and easy-to-interpret parameters. The significance of indicators derives from their use to describe, analyze, and present scientific information. Environmental indicators track changes in the quality and condition of the air, water, land, and ecosystems. Sustainability indicators go beyond environmental measures by including considerations of human health and welfare and economic conditions, as well as the inter-relationships between these domains. Sustainability indicators also provide insight into the relationship between current conditions, pressures, trends and responses. One indicator framework that adopts this approach is the DPSIR framework. It provides a general framework for organizing information about **D**riving forces of environmental change (e.g. industrial production), **P**ressures on the environment (e.g. discharges of waste water), **S**tate of the environment (e.g. water quality in rivers and lakes), **I**mpacts on the population, economy, ecosystems (e.g. water unsuitable for drinking), and **R**esponse of the society (e.g. watershed protection)[43].

[42] Powers, J. (2007) A Proposal for Developing NESCS: a Non-market Ecosystem Services Classification System, draft July 31, 2007

[43] DPSIR Framework Tutorial Page The Cities Environment Reports on the Internet (CEROI) Programme website: http://www.ceroi.net/reports/arendal/dpsir.htm

Integrated models are useful with regard to indicators in two respects: the selection of indicators provides a goal for modeling in that they guide modelers about what information is expected from their models; and models are used to represent and explore the complex cause-effect relationships used to select indicators and understand the inter-relationships among them[44]. The advantages of using an integrated modeling approach in developing and analyzing indicators have been identified as[45]:

- "showing how the various indicators are interlinked (linkages within the cause-effect chain of an issue (vertical integration) and between different issues (horizontal integration));
- yielding insights into the relevance and dynamic behavior of indicators (behavioral patterns of social, economic and environmental systems);
- enabling projections for sustainable development (long-term trends for social, economic and environmental indicators);
- identifying critical system variables and offering a guide for the selection and aggregation of indicators;
- resulting in a more comprehensive set of indicators, where model variables which appear to be of pivotal importance for trend projections are not yet part of the existing set of indicators;
- serving as a guide for the further development of the integrated modeling framework. Such coherent and integrative information can only be generated by an interconnected framework of indicators".

The advantages may also include providing the framework by which to develop/test the feasibility of applying "Reconstructed Exposure" techniques to produce useful "sustainability indicators".

[44] Ewert. F.A, van Ittersum, M.K., Bezlepkina, I., Oude Lansink, A.G.J.M, Brouwer, F.M. et al. (2005) Development of a conceptual framework for integrated analysis and assessment of agricultural systems in SEAMLESS-IF, SEAMLESS Report No.1, SEAMLESS integrated project, EU 6th Framework Programme
[45] Ibid

APPENDIX: STATE OF THE ART AND PRACTICE IN INTEGRATED MODELING AND ASSESSMENT

A.1 Experiences outside EPA

NSF Environmental Observatories Projects:

The National Science Foundation (NSF) is planning a number of environmental observatory and research networks. These projects are motivated by the recognition that, despite the existence of federal, regional, state, and local monitoring and assessment programs, "there remains a critical need for more integrated and comprehensive approaches to understanding and analyzing environmental processes that ultimately will help us better manage and improve the quality of air, land, and water resources."[46] These initiatives include the National Ecological Observatory Network (NEON), the Ocean Observatory Initiative (OOI), the Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI), and the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER).

These projects are at different stages of planning and implementation. As a coordinated group of projects, it is expected that these initiatives would be able to provide "the integrated data sets, models, and predictive capability necessary to adequately understand and guide effective management of our nation's environmental resources in a setting where large-scale, even global factors, must be considered."[47] CUAHSI and the CLEANER Project Office have formalized their strategic alliance to seek Major Research Equipment and Facilities Construction (MREFC) funding from the National Science Foundation (NSF) for the WATer and Environmental Research Systems (WATERS) Network. Through the construction of an integrated system of distributed observatories that use advanced modeling and real-time, adaptive data management, the network aims to provide scientific understanding to assure adequate and safe water for human use and economic well-being while protecting the integrity of aquatic ecosystems[48]. A critical component of the WATERS Network will be to enable multi-scale, dynamic, and predictive modeling of water, sediment, and water quality. Because of the large scale, complexity and great number of stressor sources involved, this project group seems to be a natural environment to test the feasibility and utility of applying "Reconstructed Exposure" techniques to link "indicators/biomarkers" to "sources" for source identification and prioritization for address, and to clarify the "environmental picture".

[46] National Research Council (2005) CLEANER and NSF's Environmental Observatories. Washington, D.C.: National Academies Press
[47] Ibid
[48] WATERS Network News May 2007

The Global Earth Observation System of Systems:

"This is the next frontier of human productivity. We've had the agricultural era, the industrial era, the information age. The next era is the era of interoperability"[49]

The Global Earth Observation System of Systems (GEOSS) is envisioned as a large national and international cooperative effort to bring together existing and new hardware and software, making it all compatible in order to supply data and information. Central to the GEOSS effort is the integration of data (from remote and in-situ monitoring and models), and the transformation of that data into meaningful information to provide a unified picture, and to allow global access to and sharing of that data to meet user needs and achieve societal benefits. The GEOSS architecture, illustrated in Figure A1, describes how components fit together to produce an end to end system capable of providing data and information that will better satisfy requirements than the individual components, systems or databases from which it is composed. In the implementation of GEOSS, increased sharing of methods for modeling and analysis needed to transform data into useful products will be advocated.

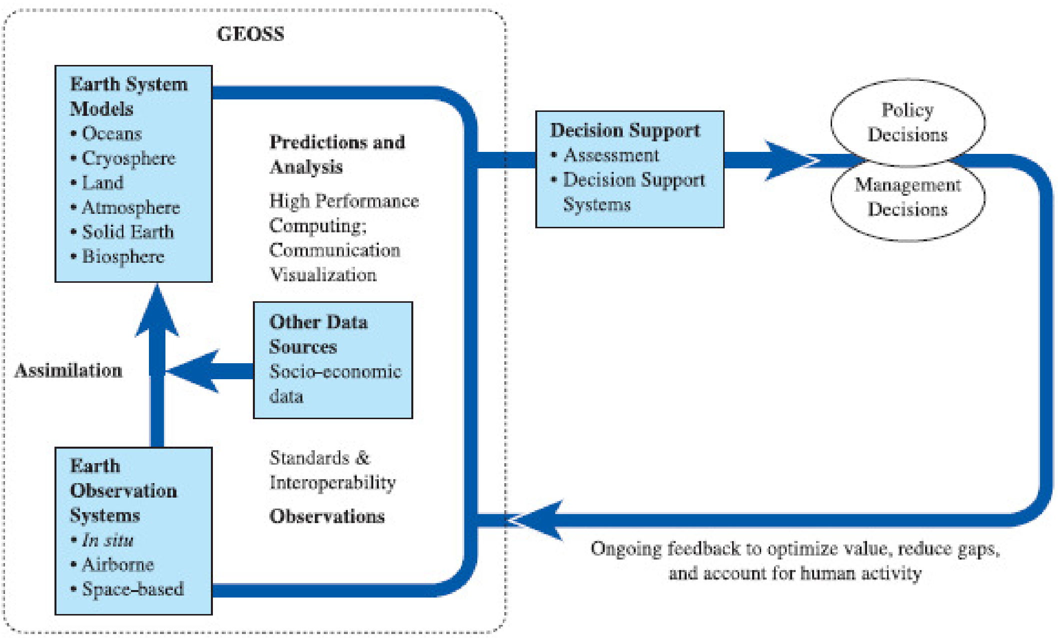

Figure A1: GEOSS Architecture[50]

[49]Michael O. Leavitt, Former EPA Administrator, Secretary, Dept of Health & Human Services. Keynote Address to the 2005 Public Stakeholder Workshop of the Interagency Working Group On Earth Observations
[50] Group on Earth Observations (2005) Global Earth Observation System of Systems, GEOSS: 10-Year Implementation Plan Reference Document, ESA Publications Division

European Union:

OpenMI

The Open Modelling Interface and Environment (OpenMI) is a standard for model linkage in the water domain. It was developed through Harmon-IT, a research project implemented during the period of 2002-2005, supported by the European Commission under the Fifth Framework Programme. The main driver for the development of the OpenMI standard was the European Union's Water Framework Directive that calls for an integrated approach to water management throughout Europe. Model integration was found to be essential to operationalizing this concept, by helping to enhance understanding and prediction of process interactions. The OpenMI standard defines an interface that allows time-dependent models to exchange data at runtime. When the standard is implemented, existing models can be run in parallel and share information at each time-step. This feature helps to address the following types of model integration[51]:

- Link models from different domains (hydraulics, hydrology, ecology, water quality, economics etc.) and environments (atmospheric, freshwater, marine, terrestrial, urban, rural, etc.);
- Link models based on different modeling concepts (deterministic, stochastic, etc.);
- Link models of different dimensionality (0, 1, 2, 3D);
- Link models working at different scales (e.g. a regional climate model to a catchment runoff model);
- Link models operating at different temporal resolutions (e.g. hourly to monthly or even annual);
- Link models operating with different spatial representations (e.g. networks, grids, polygons);
- Link models using different projections, units and categorizations;
- Link models to other data sources (e.g. databases, user interfaces, instruments);
- Link new and existing (legacy) models with a minimum of reengineering;
- Link models running on different platforms (e.g. Windows, Unix and Linux)

OpenMI is now available as open source software. The developers' long-term vision is that the OpenMI "should become the European and global standard for model linking in the environmental domain."[52] Current development and maintenance is being undertaken through the OpenMI-LIFE project in the Life Environment Programme.

[51] Moore, R., Gijsbers, P., Fortune, D., Gergersen, J., Blind, M. (2005) OpenMI Document Series: Part A Scope for the OpenMI (version 1.0), HarmonIT

[52] The Open-MI Life project website: http://www.openmi-life.org/

SEAMLESS

SEAMLESS (System for Environmental and Agricultural Modelling: Linking European Science and Society) is a large (15 million Euro) integrated project funded under the Global Change and Ecosystems sub-priority of the European Commission's Sixth Framework Programme (FP6)[53]. This project, which involves 28 research institutions from thirteen European countries along with two partners from Mali and the USA, aims to develop a computerized, integrated methodological framework (SEAMLESS-IF) to compare alternative agricultural and environmental policy options. SEAMLESS will facilitate the process of assessing key indicators that characterize interactions between agricultural systems, natural and human resources, and society[54]. SEAMLESS-IF will rely on a software framework (SeamFrame) to build applications to support modeling, decision support and policy-making. The overall design of SeamFrame is open, re-usable and extensible in order to maximize its potential of being used and adopted by modelers and researchers outside the initial core of SEAMLESS participants. The architecture of SeamFrame is shown in Figure A2. The "SeamFrame Core" is composed of a series of sub-systems and modules[55]:

- The *Domain Manager Framelet*: provides a programming interface to create data structures that will be used by models to define and characterize their inputs, outputs, states and parameters. These data structures (named Domain Classes) are built on top of a set of ontologies that describe the agri-environmental modeling domain. The model equations will be semantically denoted by means of Semantic Web technologies such as RDF and Ontologies. This will open the model structure to automated processing, leading to the possibility of searching models according to their specifications - where model linking and composition will be greatly facilitated.
- *The Model Manager Framelet:* provides a set of base classes to create models and a set of transformations to process a model in a declarative format to produce a binary object.
- *The Tool Maker Framelet*: provides a set of abstract interfaces to implement processing tools that operate on the models and data. These tools include the simulation and the optimization engines, data processors and graphers.

SeamFrame interacts with the Seamless Knowledge Base, where Ontologies, Data Structures, Models, Tools and Workflows are stored. The SeamFrame core is used by the SeamFrame development environment that consists of the Modelling Environment and of the Processing Environment:

[53] The SEAMLESS project website: http://www.seamless-ip.org
[54] Ewert. F.A, van Ittersum, M.K., Bezlepkina, I., Oude Lansink, A.G.J.M, Brouwer, F.M. et al. (2005) Development of a conceptual framework for integrated analysis and assessment of agricultural systems in SEAMLESS-IF, SEAMLESS Report No.1, SEAMLESS integrated project, EU 6th Framework Programme, contract no. 010036-2, www.seamless-ip.org
[55] Rizzoli, A.E., Svensson, M.G.E., Rowe, E.C., Donatelli, M., Muetzelfeldt, R. et al., (2005) Modelling Framework Requirements, SEAMLESS Report No.6, SEAMLESS integrated project, EU 6th Framework Programme, contract no. 010036-2, www.seamless-ip.org

- *The Modelling Environment* is a software application that allows the modeler to build, test, edit, store and retrieve models, making use of the background facilities provided by the Model Manager and the Domain Manager,
- *The Processing Environment* is a software application that creates "workflows" of operations.

The first prototype of SeamFrame has been produced after 1.5 years of the project. OpenMI is used as the interface for model integration. The next steps towards the second prototype will concentrate on further advancing the technical implementation of indicators and models by using ontologies.

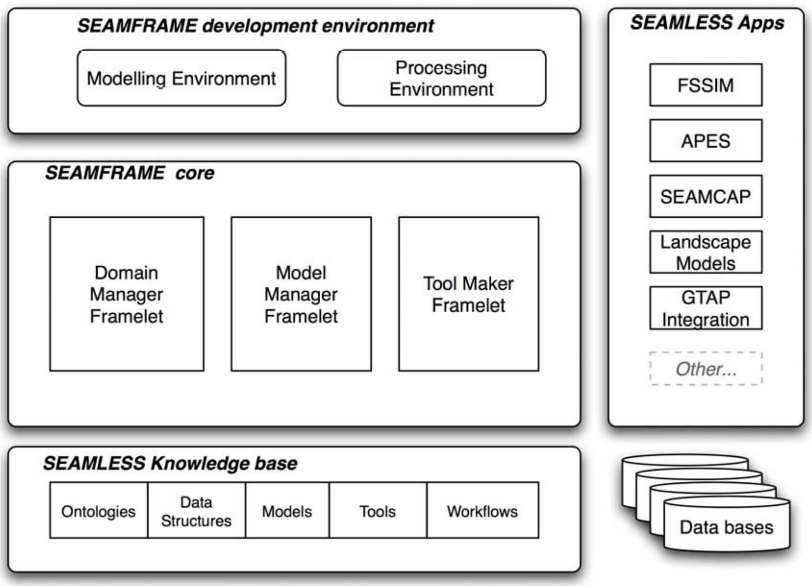

Figure A2: The SeamFrame architecture, with its development environment, the knowledge base, and the end-user applications

Regional and Global Integrated Environmental Assessments

The field of integrated environmental assessment, which originated in scientific and public policy efforts to understand and control acid deposition, has been growing steadily since the 1970s. The scope of integrated assessments has expanded beyond the original area of sulfur emissions and acid rain to encompass assessment of oxidized and reduced nitrogen and volatile organic compounds to address acidification, eutrophication and ground level ozone. The associated integrated modeling efforts have consequently involved greater levels of complexity, covering multiple spatial and temporal scales and inter-relationships between different processes. Integrated assessment modeling is also inter-disciplinary, capturing the dynamics of natural and anthropogenic systems and the decision analytics involved in economics and policy[56].

A number of global environmental assessments will be released by different organizations over the course of 2007 through early 2008. These include the fourth Global Environmental Outlook (GEO-4) Assessment by UNEP, the OECD Second Environmental Outlook and the fourth Assessment Report of Climate Change by the Intergovernmental Panel on Climate Change (IPCC). Each assessment has a specific focus and different methodological approach. However, all integrated environmental assessments rely on modeling resources to support the assessment of both the state of the environment and the consequences of environmental policies. To illustrate the role of integrated environmental assessments at various stages of the environmental management process, Table 1 has been proposed[57].

Table A1: The role of integrated environmental assessments in environmental management

Risk management function	**Content**	**Single vs. interdisciplinary science/ models**	**Policy Involvement**	**Role of Integrated Environmental Assessments**
Monitoring A	Monitoring environmental media and processes, driving forces of changes in them	Single	None	None
Risk assessment	Identify nature, causes and implications	Largely single	Moderate	Emerging
Response assessment	Identify allies and rank options	Interdisciplinary	High	Key
Goal and strategy formulation	Establish objectives and strategies to achieve them	Interdisciplinary	High	Key
Implementation	Realize and execute strategies	Largely single	Executive routine	Moderate
Evaluation	Assess actors' performance	Currently single	Executive routine	Currently moderate
Monitoring B	Monitoring effects of policies, compliance of actors	Largely single	High	moderate

[56] Oxley, T. and ApSimon, H.M. (2007) Space, time and nesting in Integrated Assessment Models, Environmental Modelling and Software, 22: 1732-1749

[57] Toth, F. and Hizsnyik, E. (1998) Integrated environmental assessment methods: Evolution and applications. Environmental Modeling and Assessment, 3: 193-207

A.2 Experiences in EPA

Integrated Modeling System for Human and Ecological Exposure and Risk

In 1996 the Office of Solid Waste (OSW) and the Office of Research and Development (ORD) established a formal partnership to develop an integrated modeling system to serve the regulatory assessment needs of the Hazardous Waste Identification Rule (HWIR). The goal of the HWIR was to determine "safe" contaminant concentration levels for waste streams entering land-based waste management units (WMUs). The threshold levels were required to be protective of human and ecological receptors located in the impact area surrounding the WMUs. The HWIR was a national ruling and the contaminant thresholds were required to apply under all environmental settings where WMUs could be placed. In response to this need, OSW and ORD designed and implemented a state of the art modeling system that consisted of a set of individual science modules that together simulated the source to risk continuum including contaminant release from WMUs to the environment, subsequent contaminant multi-media fate and transport, aquatic and terrestrial foodweb mechanics, and human and ecological exposure and risk. This collection of linked science models is named the Multi-media, multi-pathway, multi-receptor Risk Analysis (3MRA) modeling system. To manage the execution and data flow among the science modules, 3MRA was contained within a modeling framework, or infrastructure, known as FRAMES (Framework for Risk Analysis in Multi-media Environmental Systems). Recently, a second phase of development was initiated that included the formal design and implementation of the Data for Environmental Modeling (D4EM). D4EM is focused on the automated access, retrieval, and processing of the large volume of data needed to run integrated modeling systems such as 3MRA. Figure A3 illustrates the conceptual design of the integrated system that includes FRAMES, 3MRA, and D4EM. The software system is designed specifically to meet criteria related to reuse, interoperability, quality assurance, and extension. Major components are implemented with Application Programming Interfaces (APIs) that facilitate standard access protocols as well as provide for application within other modeling systems.

Figure A4 illustrates the regulatory decision context for FRAMES – 3MRA as it was applied to the Hazardous Waste Identification Rule. Decision-makers simply wanted to know the relationship between the chemical concentration in a waste-stream (the regulatory target) and the human and ecological health risk posed by disposal of the waste-stream in land-based units across the U.S. Literally millions of modeling simulations were executed using FRAMES – 3MRA. These simulations represented the full range of environmental settings where WMUs could be placed, and included probabilistic representation of all environmental variables (to allow characterization of uncertainty). Results from these individual simulations were collected in a decision support database designed to provide the decision maker only the information they required. The HWIR decision support interface (Figure A4) allows the decision-makers a graphical means by which to determine the percentage of sites across the U.S. that would be protective of human and ecological health as a function of chemical concentration in the waste-stream. This interface allows the decision-maker to appreciate the quantitative relationship between regulatory thresholds selected and the resulting potential risk incurred. Furthermore, the decision-maker can view this relationship as a function of other elements of the assessment. For example, by tapping into the decision support database containing the simulation results, the decision-maker can view the concentration – risk relationship for human health for any combination of waste chemical content, waste management unit type, exposure pathway, receptor type, cohort type, percentage of population protected, and risk level. In addition, the decision-maker can easily view the relationship as it applies to protecting receptors within a specified distance of the disposal unit. A similar interface is available to illustrate the concentration – risk relationship for combinations of important factors related to ecological risk. This system illustrates the ultimate power of integrated modeling to provide specific decision support information based on a comprehensive modeling-based assessment of the relevant environmental systems.

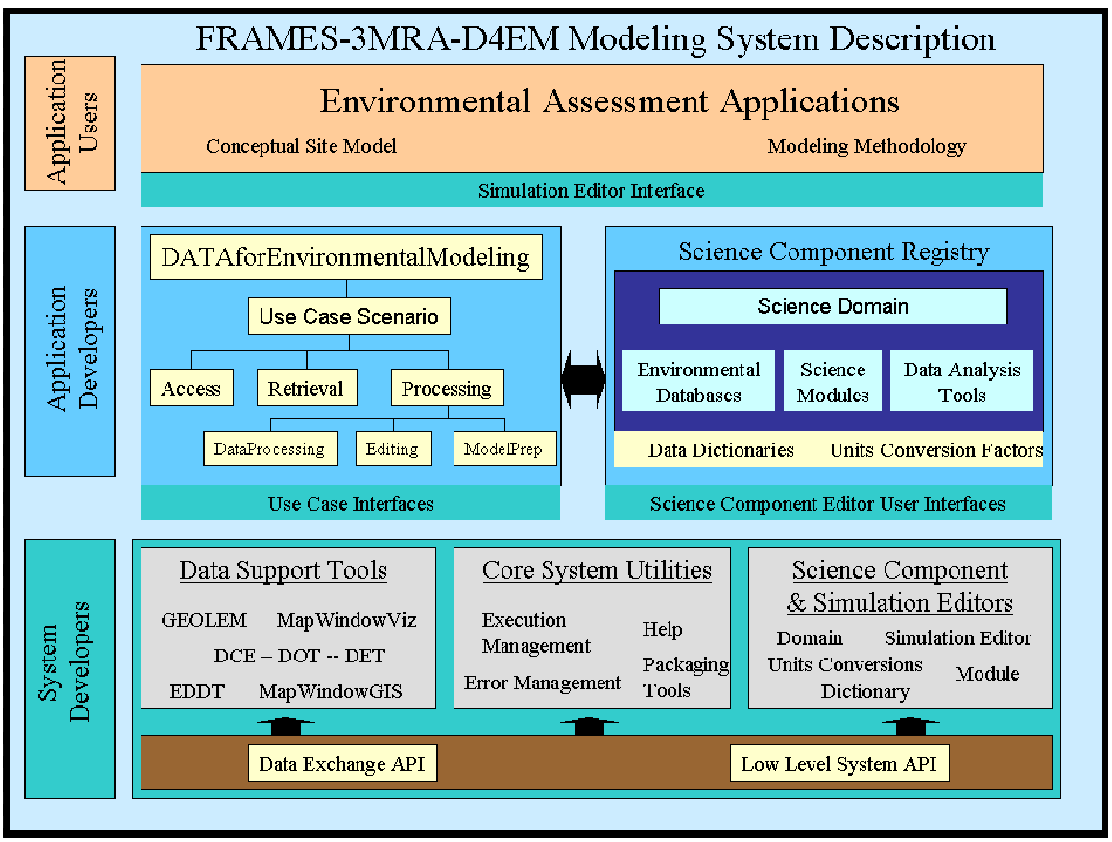

Figure A3: FRAMES-3MRA-D4EM Modeling System Description

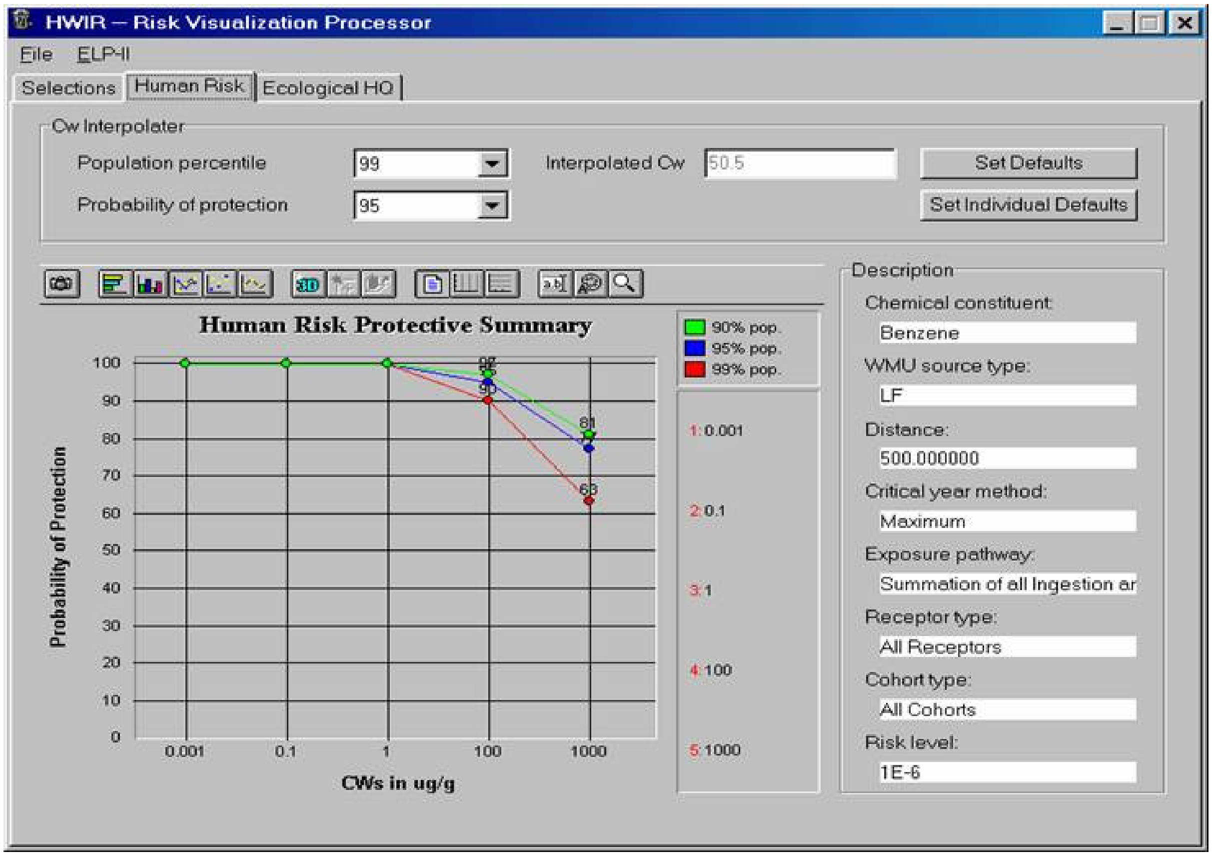

Figure A4: Decision Support Interface for FRAMES – 3MRA for HWIR Assessment

Development of the Clean Air Mercury Rule: A National-Scale Example

The Clean Air Mercury Rule (CAMR), promulgated on March 15, 2005, was the first-ever rule to control mercury emissions from coal-fired power plants[58]. The Regulatory Impact Assessment conducted by EPA during the development of the CAMR regulation provides one of the first examples of an integrated environmental analysis used for regulatory decision-making. Modeling conducted as part of this analysis ranged from regional scale atmospheric chemistry modeling using the CMAQ model to costs projections associated with different control strategies using the IPM model. Under the CAMR, each state was assigned an emissions "budget" for mercury and would have been required to submit a State Implementation Plan (SIP) detailing planned reductions in emissions from its coal-fired power plants.

The analysis used by EPA in the Regulatory Impact Assessment (RIA) involved the following multi-media modeling linkages (see also Figure A5):

1. EPA used the Community Multi-scale Air Quality Model (CMAQ) with global boundary conditions from the GEOS-Chem model to simulate the fraction of mercury deposition in the U.S. attributable to coal-fired power plants and project changes in mercury deposition by the year 2020 from implementation of the CAIR and CAMR regulations.
2. EPA modeled the reductions in fish mercury concentrations attributable to emissions from coal fired utilities by assuming that for freshwater systems where the primary source of mercury is atmospheric deposition, reductions in mercury concentrations in water-bodies and fish at steady state is proportional to the reductions in atmospheric deposition (the Mercury Maps Model).
3. To investigate uncertainty around this assumption and to model the temporal response of freshwater ecosystems to changes in mercury deposition, EPA's ORD-NERL loosely coupled atmospheric (CMAQ), watershed (GBMM), water body (SERAFM/WASP), and bioaccumulation (BASS) models for mercury applied to five case-study ecosystems with diverse physical, geochemical and biological characteristics.
4. EPA also modeled how projected changes in fish tissue mercury concentrations affected exposure of recreational anglers and their families (i.e., prenatally-exposed children of freshwater anglers).
5. To relate these modeled changes in MeHg exposure to IQ decrement, US EPA first applied a model relating daily ingestion rate and maternal hair Hg concentration, and then a dose-response model.
6. EPA translated these IQ decrements into monetary losses by evaluating foregone future earnings of affected individuals, basing its estimates on a regression model relating IQ levels, educational

[58] The CAMR rule (in conjunction with the Clean Air Interstate Rule or CAIR) would have resulted in a 70% decline in mercury emissions in the United States relative to 2001 emissions by the year 2020. On February 8, 2008, the U.S. Court of Appeals for the District of Columbia Circuit vacated CAMR. On October 17, 2008, EPA filed a petition with the Supreme Court asking the Court to review the D.C. Circuit's February 8 decision. The Supreme Court has not yet acted on that petition. Further, on July 11, 2008, the D.C. Circuit Court of Appeals vacated CAIR. On September 24, 2008, EPA and other parties in that case filed motions asking the court to reconsider its July 11 decision. The court has not yet acted on those petitions. The DC Circuit's vacatur of CAMR was unrelated to the modeling conducted in support of the rule.

attainment, and expected future earnings. Calculated "benefits" associated with the CAMR rule were discounted over time period required for reductions in modeled fish concentrations to be achieved.

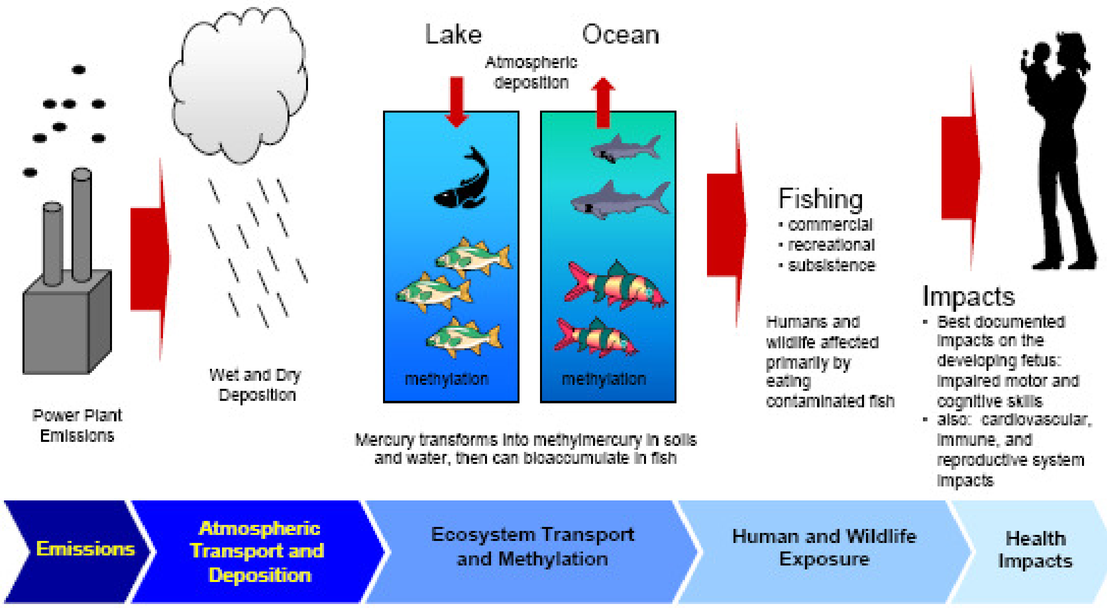

Figure A5: Schematic of the processes covered in the development of the CAMR[59]

[59] Courtesy: Tamara Saltman, OAR

Chesapeake Bay Program: A Regional- Scale Example

The essential water quality problem in the Chesapeake is eutrophication, or over-enrichment of estuary waters that results in low bottom dissolved oxygen, excessive levels of algae, and poor water clarity. To address this problem, the partnership of Federal and State governments in the Chesapeake Bay Program (CBP) committed to the restoration of the Chesapeake ecosystem. The restoration effort is guided by three water quality standards, dissolved oxygen, chlorophyll, and water clarity, that support living resources of fish and benthos, a healthy trophic system, and underwater grasses, respectively. The CBP has been applying increasingly sophisticated integrated models to support restoration for more than two decades. The first integrated models were relatively crude, being nothing more than a simple linkage of a watershed model and a model of the estuary. As the scope and sophistication of decision-making grew in the Chesapeake, commensurate with increased challenges posed by the increased population and growth in the region, the integrated models being used now include models of the airshed, watershed, estuary, living resources, and climate change. For EPA and the Chesapeake Bay Program this has been a process of "learning by doing".

The essential purpose of CBP integrated models is to answer the basic questions of the decision-makers, i.e., the integrated models are tailored to the nature of the decision and to the desired level of analysis, namely: (1) What input levels of nitrogen, phosphorus, and sediment will achieve the Bay water quality standards?; (2) What are the major loads and how do they compare to each other , including atmospheric pollutant sources?; (3) How are the pollutant loads from all sources ranked?; and (4) What are the most cost effective reductions considering the different loads from different media? The questions posed set the frame and scope of the integrated models to be applied to answer these questions.

As indicated, the current CBP integrated models include a set of models of the airshed, watershed, estuary, living resources, and climate change (See Figure A6). Chesapeake Bay Program decision-makers also want management of local streams and watersheds to be efficiently integrated into the larger regional Bay water quality assessment and attainment of water quality standards. For this reason, the integrated CBP models are scaled to support local TMDL needs as well. This allows more cost effective and environmentally protective decisions to be made at local, State, and regional scales. Underlying all of these models is monitoring data. Indeed, when monitoring and modeling programs are done well, the integration of monitoring data and models is complete, since no credible model can be developed without calibration to observed data. By the same token, monitoring programs without supporting models are also incomplete, since modeling data allows the filling-in, and explanation of, the discrete observations, both over time and between monitoring stations. At different times, the integrated models instigated new research programs in nutrient fluxes in sediment, interactions and linkages between living resources and water quality and sediment transport mechanisms.

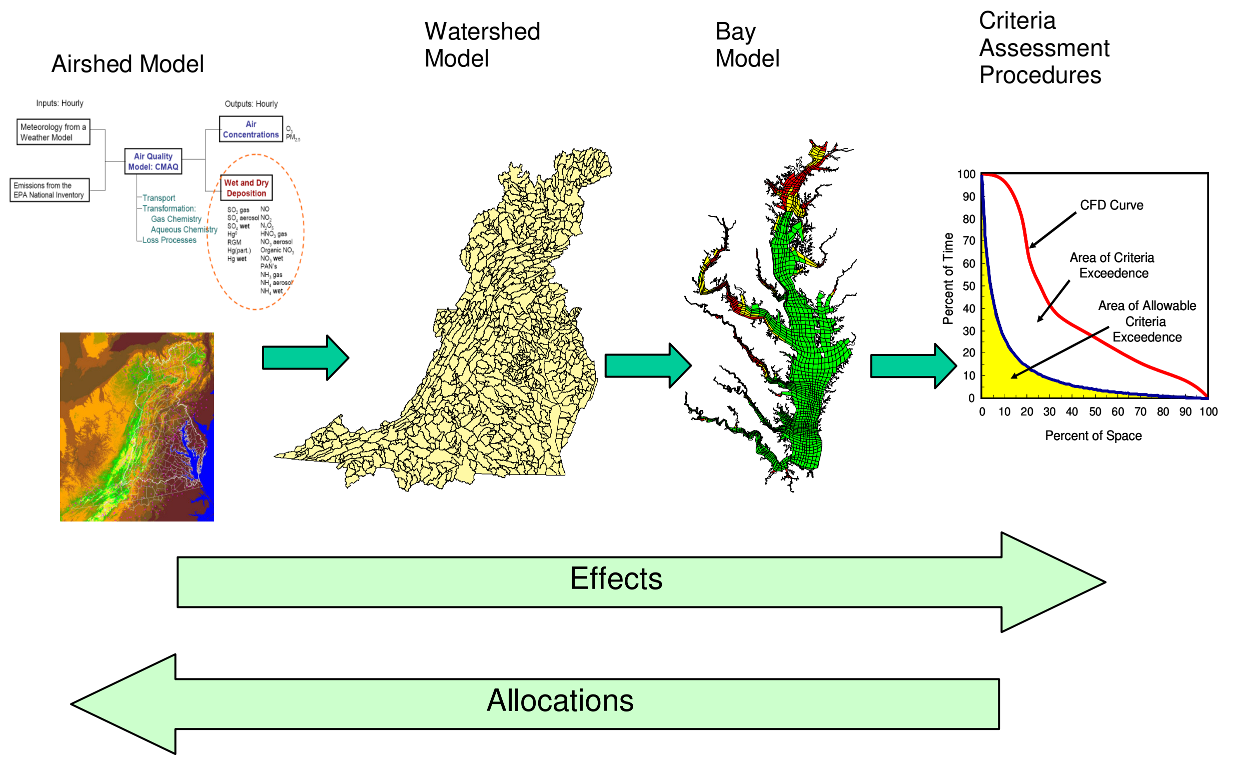

Figure A6: **The CBP integrated models of the airshed, watershed, estuary water quality and sediment transport, key living resources, and climate change**

In the CBP, it was found that the integrated modeling led to integrated decision-making by facilitating dialog among the decision-makers as they explored options in the range of meaningful, protective, and equitable reductions of nitrogen, phosphorus and sediment pollutants and the water quality and living resource improvements brought about by different aggregate levels of those pollutant reductions. The emphasis was on understanding, not on the numbers generated by the models. Questions of how to compare the cost and effectiveness of nitrogen reduction from air emissions, point sources, and non-point sources were examined. In the examination of different options, decision-makers also came to understand the essential concerns and perspectives of other decision makers from the different jurisdictions of the six State region of the Chesapeake watershed.

The Airshed Model is based on the Community Multi-Scale Air Quality modeling system (CMAQ). Runs are planned with the latest CMAQ code running on a 12 km fine grid in the Chesapeake region, with a 36km grid used for the continental scale boundary conditions. The Watershed Model is based on HSPF and is very similar to BASINS. The Watershed Model is developed as a community model, addressing regional water quality in the Chesapeake, while still capable of addressing State TMDL needs at a fine watershed scale. The Water Quality and Sediment Transport Model (WQSTM) is a three dimensional model of the tidal Bay comprised of 57,000 cells. Incorporated into the WQSTM is a full sediment transport simulation that supports PCB and other toxic modeling efforts. Living resource models of filter feeders and underwater grasses are embedded within the WQSTM. Climate change models inform inputs to both the Watershed Model and the WQSTM with respect to estimated changes in temperature and precipitation in 2030 and beyond. The Chesapeake Bay Program integrated models will be applied over the next two years (2008-2010) to examine the measures needed to achieve CB water quality standards under the projected Chesapeake land-use and populations of 2020 and 2030. The decisions made will influence plans at the federal, state, and local levels. Providing tools to aid decision-making at each of these scales is the objective of the CBP integrated models.

The primary lesson learned to date in terms of integrated modeling in the Chesapeake Bay Program is that integrated modeling for decision-making is necessary given the high cost of control of multiple nutrient and sediment load sources. Acceleration in the development and application of integrated models in the Chesapeake region is anticipated for the following reasons:

- The environmental control costs are high, and the simulation, tracking, and management of the different pollutant sources in the different media and with different approaches allows decision-making that is cost effective, more environmentally protective and allows greater efficiencies across environmental programs in air, water, and living resource management.
- The control measures are complex and involve not only different media but many distributed sources as well.
- Success in the Chesapeake can only be assured though engagement of all available pollutant control measures. The Chesapeake region has nutrient and sediment controls in the airshed and watershed that effect, in one way or another, everyone, doing everything, everywhere in the watershed.
- Fostering dialog among the six states and the federal government on sharing responsibility for nutrient and sediment load reductions and providing a level of understanding of the integrating ecosystem supports forward momentum of nutrient and sediment load controls, allowing all to plan for reductions to offset future growth in the region.

Predicting mercury levels in wildlife using the New England Regional Model (MERGANSER): A Multimedia Regional Tool

Mercury is a neurotoxin that can affect the human brain, spinal cord, kidneys and liver. Pregnant women and children are especially susceptible to mercury poisoning. Data show that many fish in New England lakes and streams have mercury levels that are unsafe for human consumption. As a result, all six New England states have issued statewide fish-consumption advisories. In addition, data show elevated mercury levels in many piscivore birds that can affect behavior and cause physiological defects as well as reduced fertility or increased rates of mortality.

To help address this problem, EPA New England has led an effort to develop a modeling tool that can be used by federal and state agencies and the academic community to assess the risk of mercury contamination in New England watersheds, and to predict mercury levels in wildlife. The idea for this modeling tool, called MERGANSER (MERcury Geospatial AssessmeNtS for the New England Region), builds on experience gained in developing the New England SPARROW (Spatially Referenced Regressions on Watershed Attributes) model that predicts nutrient loadings in rivers. Success with SPARROW suggested that similarly formulated models could be used to assess other widespread pollutants, such as mercury.

Since 2001, EPA Region I and EPA Offices of Water and Air have collaborated with a group of highly qualified mercury researchers in the Northeast to gather data and information on mercury, including its sources, transport and deposition, and environmental responses. EPA Region I recognized that the development of a SPARROW-like mercury model (MERGANSER) would be a unique opportunity to integrate models of atmospheric deposition of mercury with a rich body of high-quality data that, due to its cost, may never again be available.

MERGANSER, a fully developed conceptual model, will link multiple datasets in a GIS environment to make statistical predictions of mercury concentrations in fish and piscivorous birds in watersheds throughout New England. The model also will predict changes in mercury levels resulting from implementing various policy options. Datasets that will be used in the model include those produced or improved by the US Geological Survey for the SPARROW nutrient model (e.g., verified hydrography and delineated high-resolution watersheds), a fish-tissue database (already converted to "yellow perch equivalent concentrations" by the Vermont Agency of Natural Resources to allow concurrent analysis of data from multiple fish species), and a 2003 mercury emissions inventory by NESCAUM (Clean Air Association of the Northeast States).

A key component of MERGANSER is inclusion of a mercury atmospheric model for New England. A mercury-deposition model (100-meter grid) will be used to estimate seasonal and annual wet and dry mercury deposition (reactive gaseous mercury (RGM) and gaseous elemental mercury (GEM)) throughout New England. Results of a mercury-source-tagging model (36-km grid) will be used to estimate source contributions to mercury deposition. This will provide (1) a first-order indication of each source type's influence on deposition at the watershed and stream-reach scale for use in the MERGANSER model, and (2) a method for source attribution for GEM deposition (uptake by foliage that is one form of deposition that has been directly correlated with mercury levels in biota.

Development of MERGANSER, a multivariate regression model, will entail using a bootstrap analysis to obtain final estimates of regression-equation coefficients and the precision of these coefficients. The resultant regression equations will describe the degree of correlation of factors (e.g., watershed features, water chemistry, and mercury sources) with known mercury concentrations in fish tissue. These equations will be used to predict mercury levels in fish tissue that will then be linked to established models that characterize population-level effects in piscivore birds. Once fully developed, MERGANSER can be used to:

- Identify watershed features, such as watershed size and amount of wetlands, associated with high mercury levels in fish and piscivore birds
- Identify likely sources of mercury
- Estimate mercury levels in fish and piscivore birds at any lake or stream in New England
- Estimate mercury reductions needed from air deposition to meet water-quality criteria
- Identify optimal locations for long-term monitoring

Because MERGANSER will be GIS-based, it will be possible to produce customized, interactive displays of data at various scales useful for decision makers. Of particular importance to states will be the ability to use the model as a tool for determining whether to issue or maintain fish-consumption advisories, and for devising strategies to address those advisories. MERGANSER results also will help states to identify optimal locations for monitoring, thus maximizing use of limited monitoring resources. Moreover, model results and "lessons learned" will be useful for developing mercury models in other areas of the country where this high level of mercury data is not available.

Regional Air Impact Modeling Initiative (RAIMI): A Cumulative Risk Tool

Over 23 million tons of hazardous air pollutants are emitted each year from the 680,750 sources in the Environmental Protection Agency's National Toxic Inventory, resulting in as many as 50,000 premature deaths each year (Environmental Defense Fund data). Although required by law, federal/state/community environmental programs have not had the tools available to accurately assess or forecast the potential for health impacts posed by the real world scenario of aggregate/cumulative sources emitting contaminants; therefore, environmental regulators have not truly understood the human health and environmental consequences of their individual and collective permitting decisions.

Additionally, the two primary requests on the issue of protecting the environment are: (1) the public wants to know if the air they breathe, water they drink, and food they eat are safe; and (2) the regulators want to know, in an era characterized by tight budgets and downsizing, how best to prioritize and focus resources to make a difference and improve the environment in which we live. These concerns are warranted since it is possible to have facilities/geographic areas in compliance with all State and Federal regulations yet still have emissions that pose an adverse health effect [and vice versa].

Pollution problems identified through environmental measurements or citizen complaints are potentially based on the aggregate impact of hundreds of sources, however, solutions to the problems lie in the ability to track the pollution back to the key (greatest impacting) individual sources where it can be regulated/controlled.

The Regional Air Impact Modeling Initiative (RAIMI) is a unique methodology for determination of cumulative air pollution, cumulative health risk, and tracking air contaminants back to their source(s). The results facilitate focused, cost-effective solutions.

The innovation inherent to RAIMI is the methodology itself. Historically, regulatory agencies, industry and communities have been limited in their ability to forecast cumulative risk and track air pollutants back to their source(s). The RAIMI is a "risk assessment-based" tool that enables one to evaluate the cumulative health impact on local communities of virtually an unlimited number of emission sources. The RAIMI's power lies in its ability to both predict potential risk to individual neighborhoods and differentiate from hundreds of pollution sources, to a few where attention will yield the greatest health benefit. In addition, results from the RAIMI are generated in a fully transparent fashion such that incremental risk levels are traceable to each source, each exposure pathway (e.g. inhalation, ingestion), and each contaminant, allowing for prioritization of remedial action based on the potential impact of a contaminant and/or source, on human health.

The RAIMI is a dynamic tool. As new or refined data become available, they can be directly incorporated into the assessment to obtain revised risk estimates on practically a real time basis. This allows for the rapid identification, characterization, assessment, and management of aggregate environmental exposures that may pose the greatest health risks to the public. A community assessment that would have been deemed impractical using older techniques can be completed relatively quickly using the RAIMI.

The RAIMI tool integrates several contaminant models and databases including air fate and transport models, terrestrial fate and transport models, and exposure assessment and risk assessment models on a GIS platform. The tool is comprised of a "how to" Users Guide, a compendium of methodologies, and specifically designed software contained on a CD ROM. In application, emissions data from all known pollution sources in a particular area, both mobile (cars, buses) and stationary (factories, hospitals), are input to the RAIMI computer model that then calculates emission trajectories and deposition locations and amounts. The computer model then combines emissions data with local area land use and demographic data to estimate the potential for adverse human health impacts. The RAIMI integrated model enables successful application of a human health risk assessment methodology on a broad scale, at a level of refinement sufficient to allow neighborhoods to be differentiated and the actual pollutants and their sources to be identified.

This readily transferable tool provides an unparalleled opportunity for citizens and the public and private sectors to assess and discuss potential impacts of all air-borne environmental releases and to collaborate on protecting the state-of-the-environment and long-term land use planning.

Major program changes for which specific, immediate benefits from the application of the RAIMI include:

1. Prioritization of regulatory resources based on the source(s) contribution to human health risk (i.e., management of "worst first").
2. Improved community outreach and involvement by allowing citizens access to more comprehensive environmental analyses.
3. Objective, scientific basis for evaluating new facility sitings, operational modifications and plant expansions.
4. Provides potential platform to test/demonstrate the feasibility/utility of “Reconstructed Exposure” techniques for critical contaminant/source(s) identification and priority ranking.

A summary of three completed studies illustrating the wide applicability of the RAIMI integrated modeling system is provided in the following. Data generated from application of the RAIMI facilitated regulatory decisions that focused on environmental benefits.

1. North Little Rock, Arkansas had a history of citizen complaints surrounding a creosote plant.

- One facility, multiple emission sources
- No significant potential health impacts identified
- Odor problem existed, naphthalene identified
- Based on modeling, State elected not to pursue additional permit requirements.

2. Calcasieu, Louisiana had been identified by the National Environmental Justice Advisory Committee as an area of high concern. The Agency of Toxic Substances Disease Registry had measured dioxin levels above background in residents' blood.

- 18 major facilities, 2500 point sources
- RAIMI modeling was successfully used to validate placement of air monitors and to track highly contaminated monitored air sites back to the responsible individual sources.

3. Port Neches, Texas had very high monitored concentrations of various air pollutants dating back over 10 years.

- 16 major facilities, 1500 point sources
- RAIMI modeling was successfully used to locate specific emission source(s) that produced these very high concentrations of monitored air toxics. Prioritization of permitting and enforcement actions was successfully narrowed to focus on two key facilities and three individual sources therein.

In the broadest sense, all citizens benefit from application of the RAIMI technology, because the air breathed by all citizens will be cleaner. More specifically, citizens will be in a better position to understand the sources and potential health risks of contaminants in the air they breathe and they will be better equipped to influence permit decisions that actually impact them. The RAIMI integrated modeling system allows regulators to focus on environmental issues based upon comprehensive risk-based analyses. It also allows industry and regulators to generate a clear road map of environmental priorities, and provide local cities and chambers of commerce a tool to assist them in land-use planning decisions.

The program was designed to be fully transferable and to fulfill several site-specific project objectives including:

- prioritization of risk concerns
- refinement of national-scale risk assessments
- identification of risk trends
- determination of significance of data gaps
- tracking of emissions reduction efforts
- support of monitoring programs

The most significant obstacle to the implementation of the RAIMI program is the lack of availability and questionable quality of data in some emissions inventories. States have emissions inventories that vary considerably in data precision and accuracy. Although this obstacle can be significant, the RAIMI is set-up to identify and prioritize data gaps, providing a solution to resolving data gap issues. An additional challenge facing RAIMI implementation is past precedence and regulatory "inertia". Regulatory programs have historically focused on individual sources based on individual regulations (e.g. Clean Air Act, Resource Conservation and Recovery Act). Also, past management practices of State and Federal Regulatory Agencies have not been set-up to function across regulatory programs. By contrast, the holistic approach taken by the RAIMI requires implementation of cross-program/multi-media assessments and solutions.

A design goal fully realized during implementation of the RAIMI program was the standardization of a method by which all permitting authorities can account for and assess aggregate health effects due to multiple contaminants from multiple sources, often the subject of multiple permitting schemes but which cumulatively impact the same receptor neighborhoods.

Investigations utilizing the RAIMI methodology have been completed or are underway in Texas, Oklahoma, Wisconsin, Florida, Louisiana, New York, Arkansas, New Mexico, and Nebraska. Implementation of the RAIMI program is expected to help the EPA obtain its Urban Air Toxics Strategy goal of a 75 percent reduction in incidence of cancer attributable to exposure to hazardous air pollutants emitted by stationary sources nation-wide. In addition, it is expected that the program will significantly streamline prioritization and focusing of resources to make a difference and improve the environment.