Integrated Modeling 101

Welcome to CREM's **Integrated Modeling 101** Module!

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PREFACE

EPA's Council for Regulatory Modeling (CREM) aims to aid in the advancement of modeling science and application to ensure model quality and transparency. In follow-up to CREM's Guidance Document on the Development, Evaluation, and Application of Environmental Models released in March 2009, CREM developed a suite of interactive web-based training modules. These modules are designed to provide overviews of technical aspects of environmental modeling and best modeling practices. At this time, the training modules are not part of any certification program and rather serve to highlight the best practices outlined in the Guidance Document with practical examples from across the Agency.

CREM's Training Module Homepage contains all eight of the training modules:

- Environmental Modeling 101
- The Model Life-cycle
- Best Modeling Practices: Development
- Best Modeling Practices: Evaluation
- Best Modeling Practices: Application
- Integrated Modeling 101
- Legal Aspects of Environmental Modeling
- Sensitivity and Uncertainty Analyses
- QA of Modeling Activities *(pending)*

DESIGN

- This training module has been designed with **Tabs** and **Sub-tabs**. The “active” Tabs and Sub-tabs are underlined.
- Throughout the module, definitions for **bold terms** ❓ (with the icon) appear in the Glossary. You can also access CREM’s Modeling Glossary on the internet.
- The vertical slider feature from the web is annotated with the same image; superscripts have been added for further clarification. The information in the right hand frames (web view) typically appears on next page in the PDF version.

Vertical Slider Feature	Corresponding Figure/Text
⬍ [1]**What is a model?**	[1]**Vertical Slider #1**

Image caption.

- Similar to the web version of the modules, these dialogue boxes will provide you with three important types of information:

This box directs the user to additional insight of a topic by linking to other websites or modules

This box directs the user to additional resources (reports, white papers, peer-reviewed articles, etc.) for a specific topic

This box alerts the user to a caveat of environmental modeling or provides clarification on an important concept.

INTEGRATED MODELING 101

Building upon the concepts presented in the other Council for Regulatory Environmental Modeling (CREM) training modules, this module focuses on integrated modeling.

The module introduces the concepts of integrated modeling, provides illustrative case studies and examples of integrated modeling efforts and outlines the role of this approach in facilitating integrative systems analysis and decision making.

This module is designed to be stand-alone; a basic understanding of the concepts and terminology covered in other modules is assumed. For review, please consult the CREM Guidance Document (EPA, 2009b) or these other modules:

Additional Web Resources:

Fundamental topics of environmental modeling are covered in other modules:

- Environmental Modeling 101
- The Modeling Life-cycle

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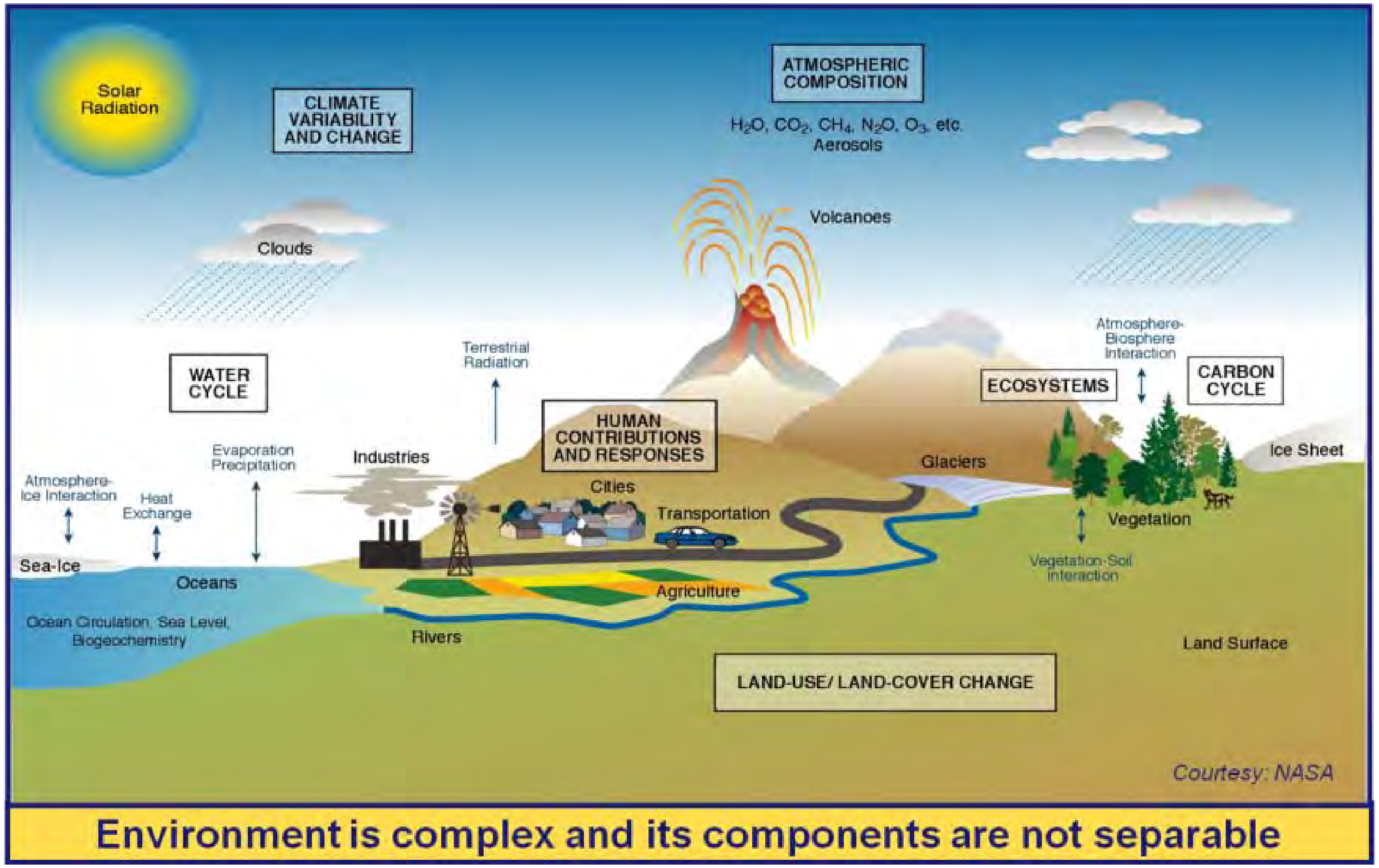

Modeling Complex and Interrelated Systems: Our surrounding environment is made up of many **systems**❷, processes and cycles that cross many media; all affected by our interaction with the environment. Integrated modeling is one approach for evaluating how these systems interact. Figure adapted from NASA.

WHAT IS INTEGRATED MODELING?

EPA (2008; 2009b) defines integrated modeling as:

> "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 can be considered linking individual **models** together linearly or by identifying co-dependencies among models **(see "Integrated Thinking" subtab).** However, integrated modeling systems go beyond the linking of two or more models; it also involves the IT infrastructure required to handle the data, information architectures, evaluation of the results, etc. **(see the "Computational Platforms" and 'Summary" sections).**

We will make a distinction in this module between computation platforms for integrated models and integrated models.

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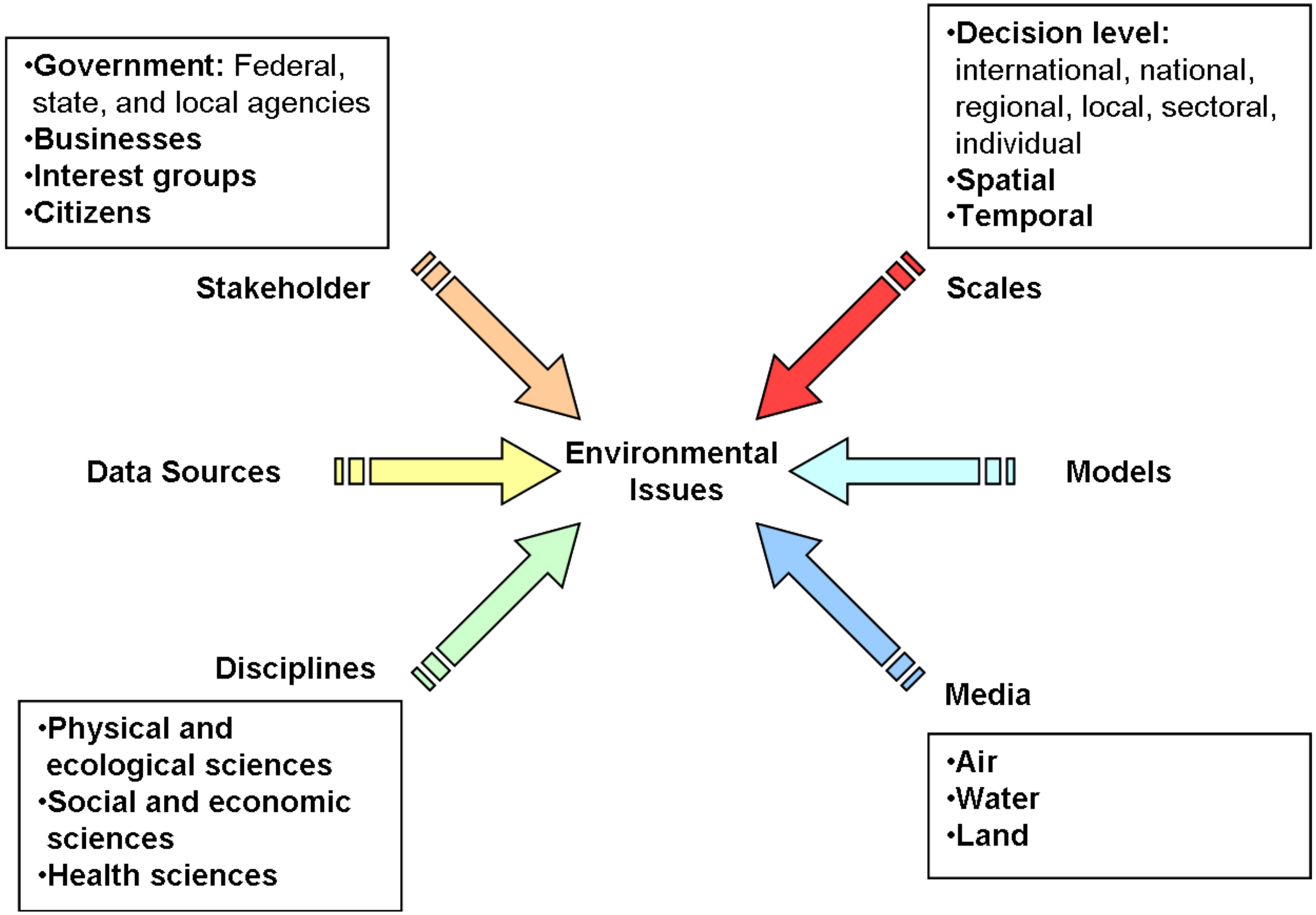


Important Environmental Issues: Aspects of model integration that should be considered when tackling environmental problems. Adapted from Parker et al. (2002).

WHY IS INTEGRATED MODELING NECESSARY?

Our environment is complex and the science necessary to understand its processes encompasses many disciplines (e.g. biological sciences, chemistry, physical sciences, ecology, economics, human behavior, etc.) that are typically isolated from one another. Similarly, the environmental policies coming out of the decision making process are often cross-disciplinary, requiring a more holistic approach of the modeling done to inform our decisions.

Therefore, the reasons for integrated modeling and a systems thinking approach can be grouped into:

- ⇕ [1]**Science Based Drivers**
- ⇕ [2]**Policy Based Drivers**

Finally, integrated modeling steps away from typical stove piped approaches to support ⇕[3]**integrated decision making** that supports sustainability.

[1]***Vertical Slider #1***

Science Based Drivers for Integrated Modeling:

Trans-disciplinary integrated modeling extends beyond the environmental sciences to include other disciplines such as economics, human behavior, land-use, valuation of ecosystem services, etc.

For example, a conventional stove-piped approach may result in impacts in other sectors that were not considered in the scope of the problem. An integrated transdisciplinary or systems thinking approach typically broadens the scope of the problem, thus including other sectors where unintended impacts (negative or positive) would be identified.

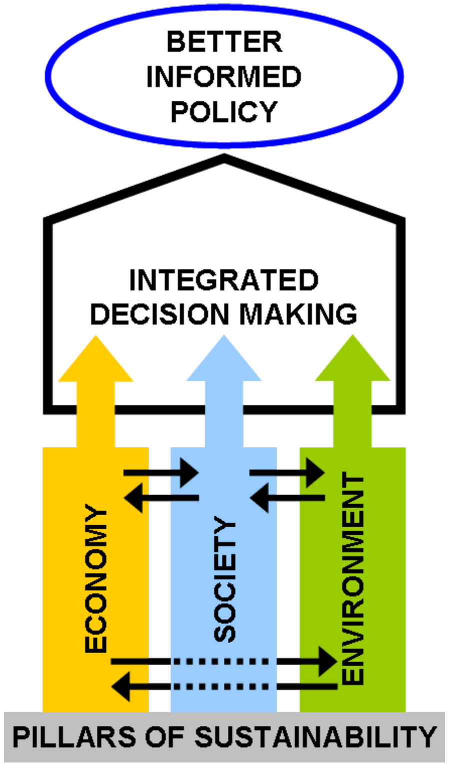
[2] *Vertical Slider #2*

Policy Based Drivers for Integrated Modeling:

Future policy-making may place greater demands on the models often used to inform them. Decisions often consider future scenarios for alternative policy implications. Therefore integrated models should have the ability to forecast future scenarios (e.g. climate) based upon alternative policy decisions. In general, modeling has been shown to be a useful tool for informing the decision making process. Integrated modeling has the ability to take current modeling capabilities and apply them in a context that is more informative, more systems based, and coordinated across many sectors.

Policy should be:		**Modeling capability:**
Forward-looking	→	Forecasting
Coordinated	→	Integrated policy analysis
Systems-based	→	Comprehensive/integrated
Info-intensive	→	Produce useful output
Incentive-based	→	Optimization analysis

[3] *Vertical Slider #3*



Integrated Decision Making:
The decision making process within each sector (e.g. economic, societal, environmental) is usually done independently, though the output from each sector is often considered during in overarching policies. There is often stove-piping within sectors (e.g. air, water and other media within the environmental sector). With integration, the sectors interact to form a strong foundation to the decision making process. A decision making process that integrates information from multiple sectors (models) could better inform policy decisions.

BENEFITS OF INTEGRATED MODELING

The integrated modeling approach is applicable to a wide spectrum of environmental assessment and management needs. Investing in the development of an integrated modeling infrastructure may result in substantial returns, with efficiencies that benefit both the modeling and the decision making communities.

Examples of the types of benefits gained from integrated modeling approaches include those in the adjacent pane.

Tol and Vellinga (1998) also note that **"the whole of integrated assessment should be greater than the sum of the disciplinary parts."** In other words, integrating models should provide added information compared to an individual (or system specific) model.

Benefits of Integrated Modeling (EPA, 2008):

- Assess risk in multiple media by evaluating multiple sources, stressors, pathways and receptors;
- Address multidisciplinary questions, or those in which social, political, and economic factors might substantially influence decision making;
- Analyze systems where processes and systems are significantly linked through two-way (or greater) coupling and feedback;
- Clarify information for decision makers without resulting in an unacceptably high level of uncertainty;
- Link source information (emissions) to ambient concentrations (whether in air, water, or soil) and, finally, to human health or ecological effects;
- Conduct cost-benefit analysis and valuation of ecosystem services;
- Weigh many alternative regulatory or management scenarios;
- Develop adaptive management strategies;
- Identify potential sources of observed environmental degradation.

EPA'S STRATEGIC VISION FOR INTEGRATED ENVIRONMENTAL DECISION MAKING

The US EPA published a white paper (EPA, 2008) that built upon a highly successful workshop organized by EPA's CREM and the Office of Research and Development's Ecosystems Research Division. This workshop aimed to initiate a broad-based dialogue on the use of integrated modeling approaches to inform environmental decision making.

The white paper proposes a strategic vision for integrated environmental decision making, supported with recommendations to achieve this strategic vision. Briefly, those recommendations included (EPA, 2008):

- Promotion and adoption of a systems approach to research efforts that support decision making
- Implementing modeling into the decision making process in a way that enhances the decision as well as stakeholder involvement
- Pursuing an organizational approach to promote integrated modeling, rather than project by project

Including integrated modeling in the decision making process could result in significant improvement in problem understanding and solution effectiveness as well as enhancing stakeholder collaboration and the transparency of decision making (EPA, 2008).

Additional Resources:

Integrated Modeling for Integrated Environmental Decision Making. 2008. EPA 100-R-08-010. Washington, DC. Office of the Science Advisor, US Environmental Protection Agency.

INTEGRATED MODELING AT EPA

Evolving regulatory focus of the US EPA from single pathway analyses to integrated modeling approaches (Whelan and Laniak, 1998; EPA, 2008).

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

ASPECTS OF INTEGRATED THINKING

The various definitions related to **integrated modeling** underscore the important concepts of an integrated, or 'systems thinking' approach.

The terms associated with 'integrated modeling' are used inconsistently in the literature, often varying from discipline to discipline. In some instances, these definitions over-lap; further contributing to the confusion. A few of the more prominent terms are identified and summarized here:

- [1]**Integrated Modeling**
- [2]**Integrated Assessment**
- [3]**Integrated Assessment Modeling**
- [4]**Integrated Environmental Modeling**
- [5]**Integrated Environmental Decision Making**
- [6]**Integrated Environmental Strategies**

In any of these definitions, 'integrated' conveys a message of multi- or interdisciplinarity or 'systems thinking'; and 'assessment' a message of policy relevance (Tol and Vellinga, 1998). Whereas 'modeling' indicates the development and/or application of simulation models.

[1]*Vertical Slider #1*

Integrated Modeling (EPA, 2008; 2009b) (#1)
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 relationships relevant to a well specified problem statement.

[2]*Vertical Slider #2*

Integrated Assessment (Parson, 1995; Weyant et al., 1996; Jakeman and Letcher, 2003) (#2)
The two defining characteristics of integrated assessment are (a) that it seeks to provide information of use to some significant decision maker rather than merely advancing understanding for its own sake; and (b) that it brings together a broader set of areas, methods, styles of study, or degrees of certainty, than would typically characterize a study of the same issue within the bounds of a single research discipline. **Briefly, integrated assessments link research to policy.**

Vertical Slider #3 [3] **Integrated Assessment Modeling (Rotmans and van Asselt, 2001; Rosenberg and Edmonds, 2005)** (#3) **Integrated assessment modeling is an analytical approach that brings together knowledge from a variety of disciplinary sources to describe the cause-effect relationships by studying the relevant interactions and cross-linkages.** Recently, it has been applied to complex environmental issues; bringing together natural science, social science and economic dimensions.	***Vertical Slider #5*** [5] **Integrated Environmental Decision Making (EPA, 2000)** (#5) Integrated decision making is a natural progression from fragmented approaches for protecting human health and the environment. Integrated thinking about complex environmental problems is at the core of this concept. The process also includes **integrating resources and analyses to address the problems as they occur in the real world, and integrating input from the public and interested and affected parties.**
Vertical Slider #4 [4] **Integrated Environmental Modeling** (#4) Integrated environmental modeling is a discipline of **developing a system of models where models from two or more academic disciplines are integrated such that they behave like a unit to external stimuli.** At least one of the models in the system is from environmental domain while others may come from other academic disciplines such as socio-economic domain. The models integrated into the system are usually developed in complete isolation from each other.	***Vertical Slider #6*** [6] **Integrated Environmental Strategies (IES) (EPA, 2004)** (#6) The IES approach enables local researchers to quantify the co-benefits that could be derived from implementing policy, technology, and infrastructure measures to reduce air pollutants and GHG emissions. Thus, **integrating environmental models with economic and health effect models to conduct a cost-benefits analysis of pollution control measures.**

CONCEPTUAL MODELS OF INTEGRATED SYSTEMS

Similar to individual model development, an integrated modeling project should start with a **conceptual model** of the system of interest.

A defining feature of integrated modeling is the holistic, or 'systems thinking' approach to solving a specific problem. Take for example the problem of hypoxia in the Northern Gulf of Mexico.

A conventional approach to characterizing the hypoxia problem might be to model pollutant loads coming from the rivers that feed the Gulf. Non-point and point sources may be identified and pollution controls could be used to alleviate loads delivered to the Gulf.

Alternatively, an integrated approach could also consider atmospheric sources, land-use changes, climate change impacts, and how different economic sectors and activities may influence the pollutant loads reaching the Gulf.

There are existing approaches which can help in the conceptualization of an integrated system. These conceptual models can help to identify how models addressing different processes can be integrated to an analysis of the whole system.

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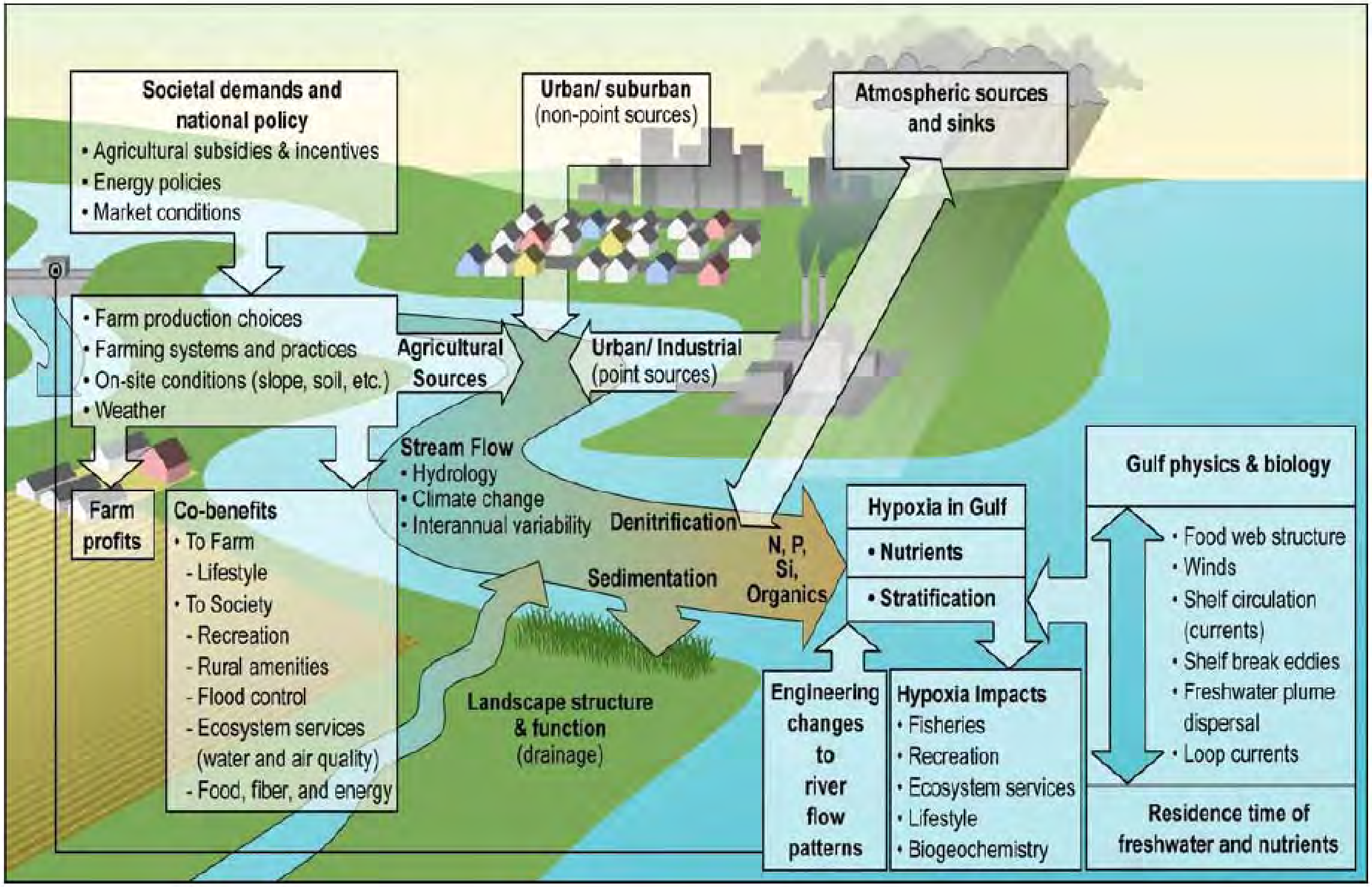
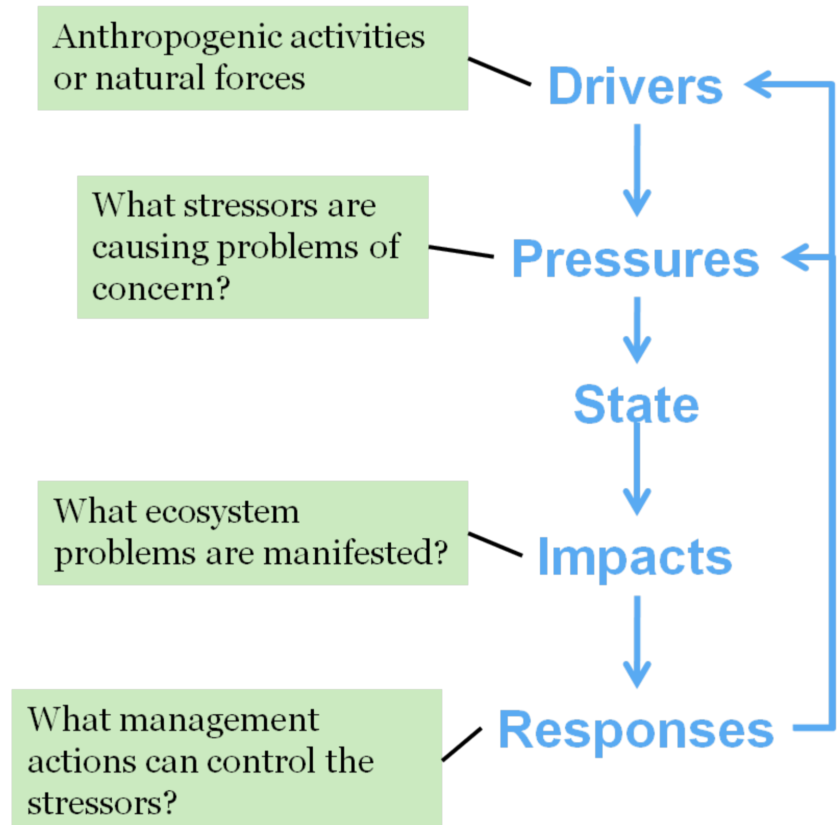


An Example of a Conceptual Model of an Integrated Approach: Complex environmental issues, like the hypoxia problem in the Northern Gulf of Mexico, may be better assessed with an integrated modeling approach utilizing information (models, data, etc.) from multiple sectors. Image adapted from EPA (2007).

DRIVER-PRESSURE-STATE-IMPACT-RESPONSE

The DPSIR approach (Smeets and Weterings, 1999) is a conceptual tool that has been found useful for organizing and simplifying the complexity of ecosystem management (Ojeda-Martínez et al., 2009). As suggested by its name, DPSIR consists of five components that inform decision making:

- **Drivers (D)** represent societal needs such as food, water, shelter and cultural connection. These needs can be identified in economic sectors.
- **Pressures (P)** are created as a result of human activities (Drivers) on the environment. Natural resource use, land-use/land-cover change, transportation networks and release of chemicals are examples of pressures.
- The **state (S)** of the environment is subject to changes brought upon by the Pressures. Measures of environmental state include concentrations of pollutants in the air, water, soil and biota, human and ecosystem health status.
- **Impacts (I)** to the environment result from changes in the State; such as changes in ecosystem function and the delivery of environmental goods and services. Impacts can also manifest in human health and the socio-economic functioning of society.
- **Responses (R)** are actions taken by society, in response to an impact (e.g, regulations). These responses can address the drivers, pressures, states or impacts.



The DPSIR approach.

A DPSIR EXAMPLE

The DPSIR approach can be applied to the development of a TMDL (Total Maximum Daily Load) conceptual model. For example, under the Clean Water Act, the development of a TMDL can be a ***response*** to an ***impact*** (non-attainment of designated use). This ***response*** is aimed at mediating a ***pressure*** (point- and non-point source pollutant or sediment loads) to effect a change in ***state*** (physical, chemical or biological characteristics of the water body).

The systems or sectors that are included in this approach include the agricultural (as non-point source of pollution), industry (point sources), environmental (plant and animal populations, ecosystem services), valuation of ecosystem services, and human behavior (recreation, waste disposal, etc.). Air circulation and weather models might also be included to account for deposition and precipitation.

Not all TMDLs are developed this way, this is just an example of how the DPSIR approach could be used to facilitate an integrated modeling approach.

Additional Web Resources:

General information regarding the Agency's TMDL program can be found at: Impaired Waters and Total Maximum Daily Loads

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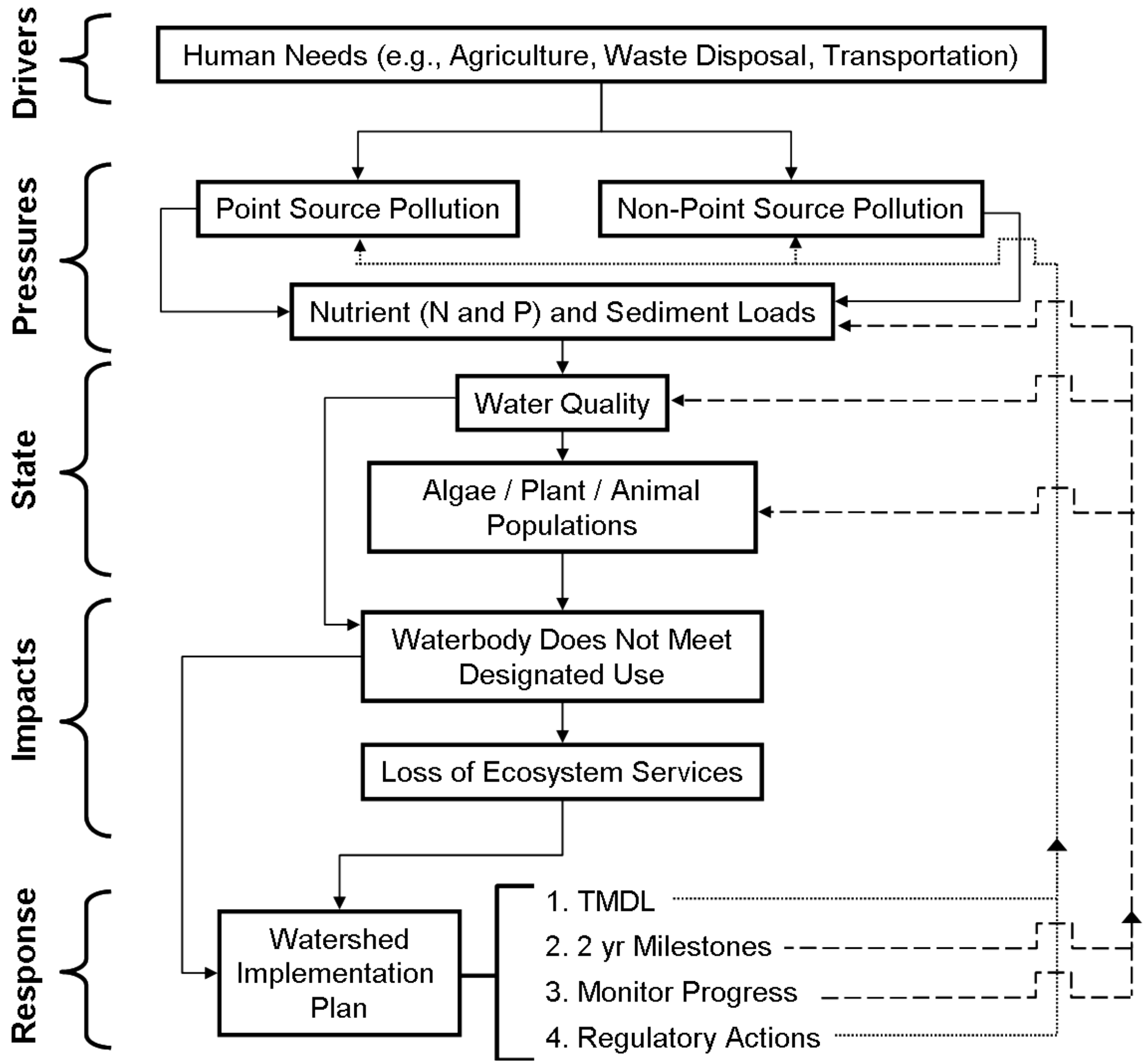

A representation of the DPSIR approach in the context of a hypothetical TMDL development problem.

DRIVER-PRESSURE-STATE-EXPOSURE-EFFECT-ACTION

Similar to DPSIR, the DPSEEA approach can help to organize information when developing an integrated modeling scheme. The approach describes six components of the environment-health chain including exposure (Smeets and Weterings, 1999; Briggs, 2003):

- **Drivers (D)** represent societal needs such as food, water, shelter and cultural connection. These needs can be identified in economic sectors.
- **Pressures (P)** are created as a result of human activities (Drivers) on the environment. Natural resource use, land-use/land-cover change, transportation networks and release of chemicals are examples of pressures.
- The **state (S)** of the environment is subject to changes brought upon by the Pressures. Measures of environmental state include concentrations of pollutants in the air, water, soil and biota, human and ecosystem health status.
- **Exposures (E)** — that take place when humans are exposed to these changed environmental conditions.
- **Effect**s **(E)** — adverse impacts on health due to these exposures.
- **Actions (A)** — policy and other interventions, aimed at reducing or avoiding these adverse health effects.

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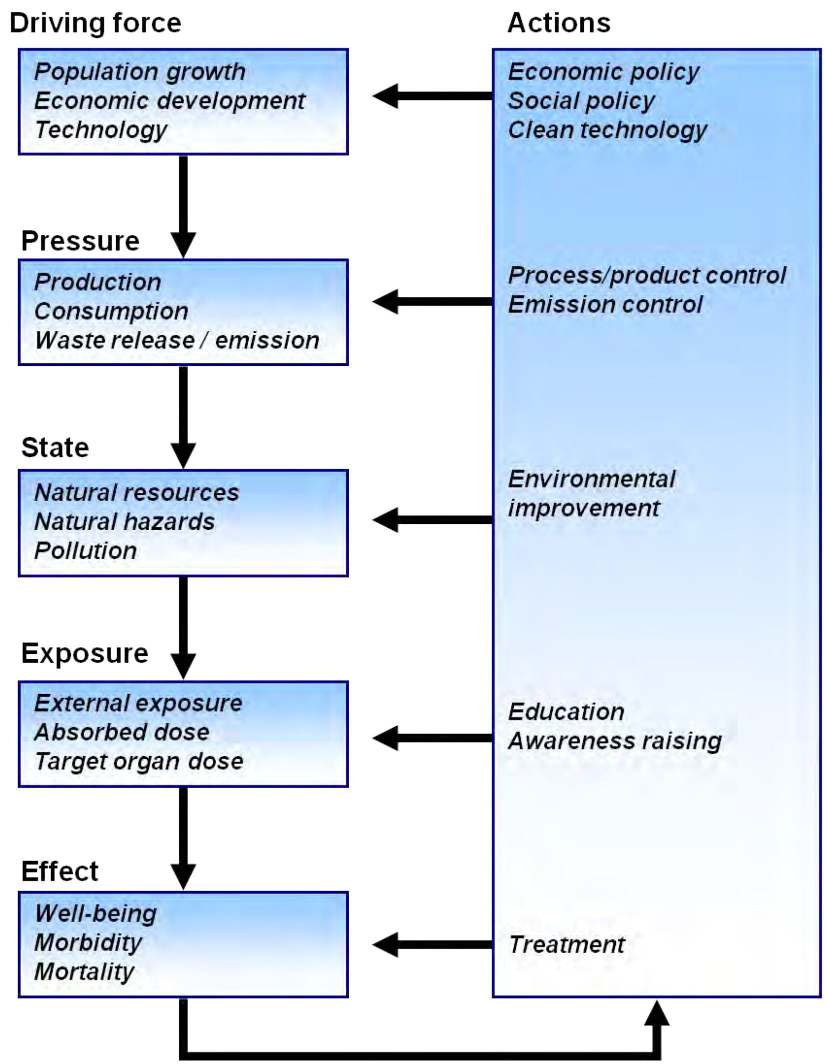

The DPSEEA approach. Adapted from Briggs (2003).

A DPSEEA EXAMPLE

The DPSEEA approach could be applied to address drinking water contamination. For example, drinking water sources, which all humans need, could become contaminated with toxic chemicals through a variety of drivers (e.g. land use changes, hydraulic fracking, and improper waste disposal). If contaminated water is ingested, generic health effects (e.g. morbidity or mortality) may develop. Appropriate actions can then be taken place along the chain to prevent further adverse health effects.

In this example, water quality models, risk assessment models, exposure models, and economic models may all be integrated to inform the policy actions.

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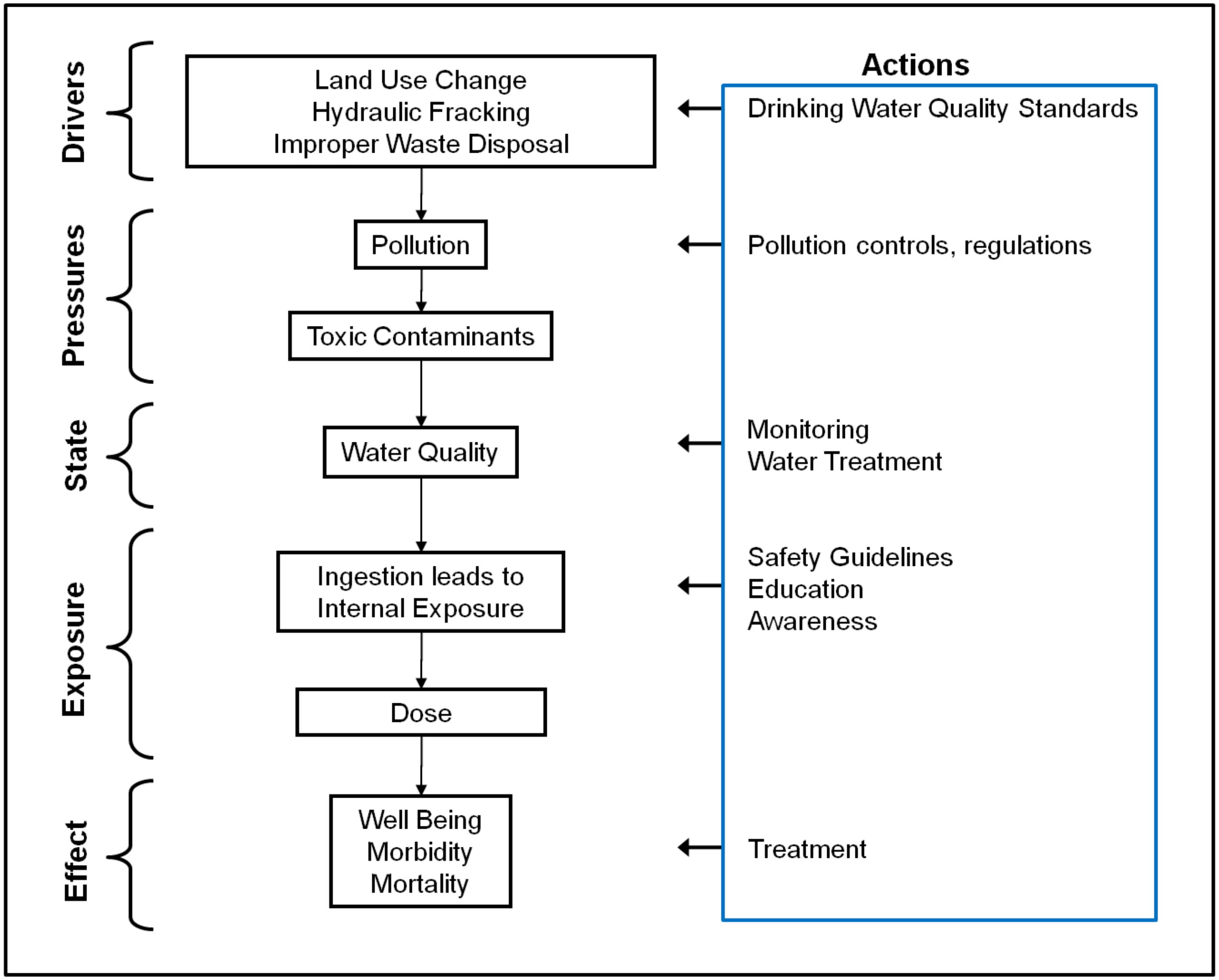

DPSEEA Example: A hypothetical example of contaminant exposure through drinking water using the DPSEEA approach. Adapted from Briggs (2003).

EXAMPLE INTEGRATED MODELING ACTIVITIES

In this section, a few integrated modeling activities are highlighted. This is not intended to be a comprehensive list, but rather provide some examples of integrated modeling systems from across the Agency.

Additional information for each of the examples is provided in next pages of the module.

Additional Web Resources:

Chesapeake Bay Program:
- CBP Home Page

NESCAUM:
- NESCAUM Home Page

BASINS:
- BASINS Home Page

Chesapeake Bay Program (CBP)

The essential water quality problem in the Chesapeake Bay is eutrophication; the over-enrichment of estuary waters that results in low bottom dissolved oxygen, excessive levels of algae, and poor water clarity.

The restoration effort is guided by three water quality standards: dissolved oxygen, chlorophyll, and water clarity. The Chesapeake Bay Program 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, the integrated models being used now include models of the airshed, watershed, estuary, living resources, and climate change.

This information was adapted from: http://www.chesapeakebay.net/

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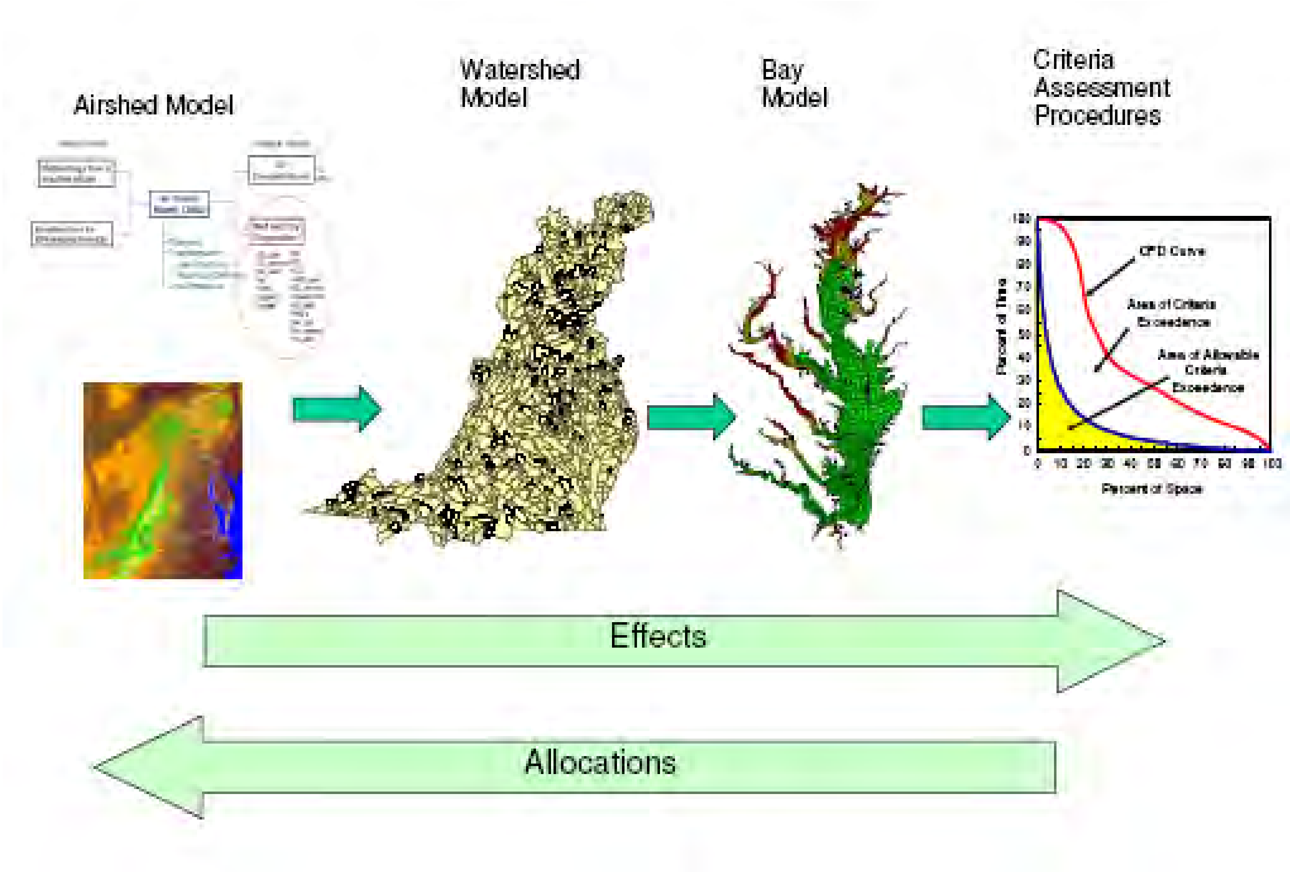


The Cheseapeak Bay Program Integrated Model: The CBP integrates models of the airshed, watershed, estuary water quality and sediment transport, key living resources, and climate change.

NESCAUM

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

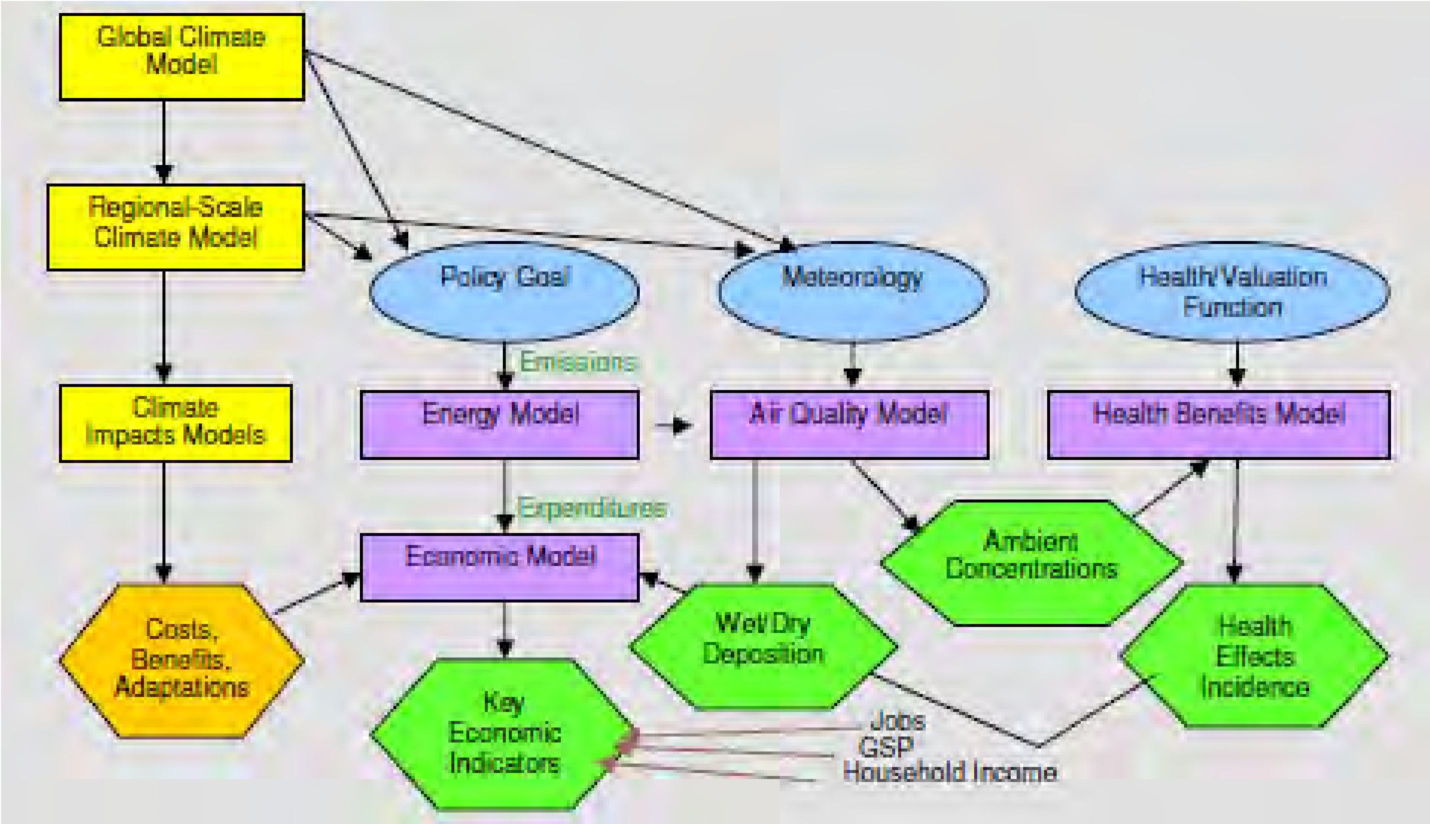
There is great need for economic, energy and environmental information to support sound energy and air quality planning at the state and regional level. This information is required to assist decision-makers in understanding the challenges presented by multi-pollutant management options and regional policy commitments. The National Risk Management Research Lab in EPA's Office of Research and Development 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).

⬍[1]**This analytical approach** 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 analysis 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 air quality standards).

⬍[2]**Additional information on the models in this example.**

(Vertical sliders are on the next two pages.)

[1]*Vertical Slider #1*



NESCAUM Conceptual Model: The integrated regional policy analysis from the Northeast States by the Northeast States for Coordinated Air Use Management (NESCAUM). For updated information please see their [Climate and Energy website](). Image adapted from EPA (2008).

[2]*Vertical Slider #2*

The integrated models within NESCAUM:

MARKAL

- MARKAL model website

REMSAD

- REMSAD model website
- Registry of EPA Applications, Models and Databases (READ)

CMAQ

- CMAQ model website
- Registry of EPA Applications, Models and Databases (READ)

BenMAP

- BenMAP model website

COBRA

- COBRA model website

BASINS - Better Assessment Science Integrating point and Nonpoint Sources

EPA's BASINS modeling integrates environmental data, analytical tools, and watershed modeling programs. BASINS supports the development of cost-effective approaches to watershed management and environmental protection (EPA, 2009a).

EPA developed the Climate Assessment Tool (CAT) for BASINS 4.0 in 2006. BASINS-CAT provides a flexible set of capabilities for modifying historical weather data to create climate change scenarios for assessing the influence of climate variability and change on water quantity and quality using the Hydrologic Simulation Program—FORTRAN (HSPF) watershed model.

The BASINS modeling system combines five components (EPA, 2009a):

- a comprehensive collection of national cartographic and environmental databases;
- environmental assessment tools (to summarize results; establish pollutant source/impact interrelationships; and selectively retrieve data);
- utilities (e.g., import tool, download tool, grid projector, post-processor, and land use, soil classification and overlay tool);
- automated watershed characterization reports (for eight different data types); and
- a suite of watershed models

MULTI-USE COMPUTATION PLATFORMS

Within the integrated modeling community, there are development efforts to construct computational platforms which will allow for (relatively) seamless linking of individual, stand-alone models (they may be referred to as components).

These platforms serve as the backbone for large and complex integrated modeling efforts. They are designed to handle data storage/retrieval, data processing, synchronization of model runs, and other communications between the individual components/models, etc.

Some of the platforms have standards for maximized inter-operability (input/output protocols, operating platform, etc.); others allow the model developers a little more flexibility.

With computational platforms, independent models can be linked together much like puzzle pieces interconnect.

Open Modeling Interface and Environment (OpenMI)

The OpenMI defines standards for model linkage in the water domain. While not necessarily a platform, models that conform to this standard are thus compatible.

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 (Moore et al., 2007; EPA, 2008).

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. The features of OpenMI help to address the types of model integration described to the right.

Additional Web Resource:

The OpenMI Life project website:
http://www.openmi-life.org/

Features of the OpenMI standard:

(Adapted from Moore et al., 2007; EPA, 2008)

- Link models from different domains (hydraulics, hydrology, ecology, etc.) and environments (atmospheric, freshwater, rural, etc.)
- Link models based on different modeling types (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)

Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES)

FRAMES is a software-based modeling system within which collections of models and modeling tools (e.g. data retrieval and analysis) are developed and applied to real world problems.

FRAMES allows models placed within its domain to communicate with each other, facilitating the passage of data, resulting in the simulation of complex environmental processes.

Additional Web Resources:

The FRAMES/3MRA model website

The capabilities of FRAMES are further discussed in another module:
Sensitivity and Uncertainty Analyses

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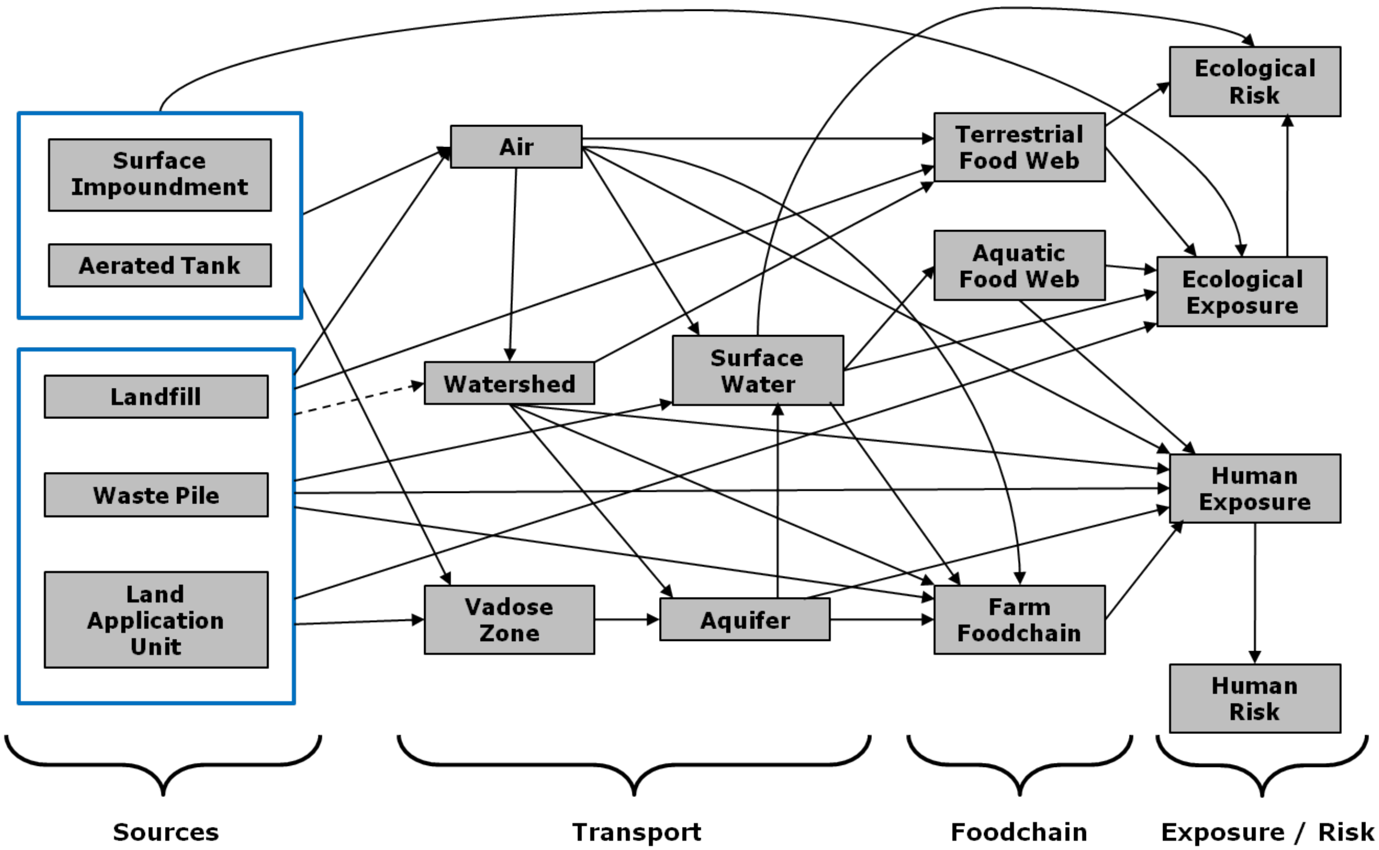

An example of the 17 science based models and their connectivity within FRAMES-3MRA. Adapted from EPA (2003).

The 3MRA Example

Multimedia, Multi-pathway, Multi-receptor Risk Analysis (3MRA) is a set of 17 modules placed within FRAMES that collectively simulate the release, fate and transport, exposure, and risk (human and ecological) associated with waste-stream contaminants deposited in various land-based waste management units (e.g. landfills, waste piles).

Object Modeling System (OMS)

The OMS is an integrated environmental modeling system developed by Agricultural Research Service of the US Department of Agriculture (see Ahuja et al., 2005).

OMS is a computer framework consisting of:

- a library of science, control, and database modules;
- a means to assemble the selected modules into a modeling package customized to the problem, data constraints, and scale of application;
- an automatic generation of a friendly user interface;
- creation of a compiled, ready-to-run, version of the package.

The platform includes many interoperability features; such as the ability to handle all data types (file extensions) that can be translated for conversion or transformation as needed.

Additional Web Resource:

The Object Modeling System website.

ADVANCED IT INFRASTRUCTURE

The focus of this module has been on conceptual and computational approaches to integrated modeling. However, a large component of integrated modeling systems extends beyond linking models together; it also includes the "IT" side of integrated modeling.

Integrated modeling is more than the models and the science they represent. The logistics of integrating models is discussed further in the "**Challenges" subtab**. However, the IT features of an integrated system might consider the bulleted items to the right.

Computational platforms or other integrated modeling IT infrastructures should be designed to handle:

- model connectivity;
- information architecture;
- framework connectivity;
- web-based access;
- system functionality;
- model evaluation and uncertainty analysis;
- education and knowledge management;
- achieving interoperability;
- automated data access, retrieval, and processing;
- the development of decision-support interfaces

CHALLENGES FOR INTEGRATED MODELING

Notwithstanding the benefits of an integrated modeling approach from a scientific and decision making perspective, there are a number of challenges to advancing the state of the art and application of integrated modeling and environmental systems analysis (EPA, 2008).

These challenges can be categorized into three groups:

- [1] **Scientific or Knowledge-Based**
- [2] **Information Technology (IT)**
- [3] **Organization and Institutional**

Additional Web Resources:

Fundamental topics are covered in other modules:

- Best Modeling Practices: Development
- Best Modeling Practices: Evaluation
- Sensitivity and Uncertainty Analyses

[1] *Vertical Slider #1*

Scientific / Knowledge-Based Challenges

Potential science-related issues in the context of integrated modeling are: design of the integrated analytical framework, **model evaluation** and **uncertainty analysis**, and education and knowledge management.

Linking multiple models together has its own set of challenges including: linking different model types (probabilistic vs. deterministic); reconciling different spatial and temporal scales; assessing uncertainty and finally applying the system of models in the correct context. Each component model, as well as the full system of integrated models, must also be evaluated (EPA, 2009b).

The practices for individual model development and evaluation discussed in other modules can be applied to integrated modeling. However, uncertainty analyses with integrated models become increasingly complex with an increased number of components (see Babendrier et al., 2005).

[2] *Vertical Slider #2*	[3] *Vertical Slider #3*
Information Technology Challenges Achieving interoperability of many models, let alone two or three, is a significant challenge for integrated modeling efforts. The scientific understanding of the processes that link models from different media (e.g. air and water) forms the basis for integration; information technology (IT) provides the mechanistic means towards an integrated solution. Some of the known issues facing integrating modeling from an IT perspective are: achieving interoperability; automated data access, retrieval, and processing; and the development of decision support interfaces (EPA, 2008). There are at least three approaches to tackle the IT challenges of integrating models: • Use of a software package framework designed for model integration such as **FRAMES** • Following a set of model integration standards, specifications, and conventions such as **OpenMI** • Hard-wiring of models without following any established standards	**Organizational and Institutional Challenges** A significant hurdle for the promotion of integrated modeling into day-to-day practices has been stove-piping of research and modeling activities. Stove-piping of research, modeling and decision making activities is a systemic challenge that hinders effective and meaningful inter-office or inter-agency collaboration. Further, organizational structures do not often facilitate cross-media interactions. Poor communication and collaboration also hinder cross-fertilization of ideas and true interdisciplinary research. However, integration of science and technology to support decision making is made possible when researchers, stake-holders, and decision makers from various sectors and disciplines come together and commit to share and implement ideas for a common purpose (EPA, 2008). Collaboration is fundamental to integrated modeling. Groups of integrated modeling teams can collaborate to develop common solutions to common science and IT challenges. This in turn would facilitate further collaboration and reuse of integrated modeling systems. From continued collaboration, a community of modelers, stakeholders and decision makers could take form.

COMMUNITY OF PRACTICE

In an effort to address these challenges and promote the benefits of integrated modeling, CREM has launched an international **Community of Practice for Integrated Environmental Modeling (CIEM).**

The CIEM aims to stimulate interactions among its members to foster learning and knowledge sharing and to spark innovation in the field of integrated environmental modeling. The CIEM will also promote integrated modeling as a means of achieving better management decisions, so that resources are used sustainably and broader impacts (often unknown during conventional, stove-piped approaches) are better understood.

One of the main goals of the CIEM is:

> *"Leveraging the knowledge and tools of the community to advance integrated modeling science and technology."*

The CIEM introduced the **iemHUB** to support their goals and the growing integrated environmental modeling community.

Additional Web Resource:

The **iemHUB** is an online community resource that supports the development, evaluation, and application of environmental models.

As a consequence of the interdisciplinary nature of environmental modeling, the iemHUB is designed to facilitate knowledge sharing, discussion and collaboration on models and tools that support multimedia and multidisciplinary analysis.

The iemHUB provides a unique environment for model access, simulation, and teaching and learning about environmental modeling.

The iemHUB Community website:
http://www.iemhub.org

SUMMARY

Integrated modeling is not simply a model building exercise. From EPA (2008):

> *"…[integrated modeling] 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."*

The [1]**integrated modeling process** includes multiple layers of integration and environmental systems analysis. EPA (2008) also identified [2]**essential qualities of integrated modeling.**

(Vertical sliders are on the next page.)

[1]*Vertical Slider #1*	[2]*Vertical Slider #2*
Processes of Integrated Modeling: • **Development of conceptual models:** Important components within each discipline should be identified and the relationships among these components (also across disciplines) should be characterized. • **Representation of information:** Development of common data formats and underlying frameworks may facilitate interoperability. • **Support to decision makers:** 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:** 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.	**Essential Qualities of an Integrated Modeling System:** • **Coherence:** Science components (data, models, methods and assumptions) are appropriately consistent across the system with respect to complexity, 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 assurance:** Procedures and methods for assuring that the selected modeling approach is implemented without error are integrated directly into the modeling approach.

YOU HAVE REACHED THE END OF THE INTEGRATED MODELING 101 MODULE.

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GLOSSARY

Calibration: The process of adjusting model parameters within physically defensible ranges until the resulting predictions give the best possible fit to the observed data. In some disciplines, calibration is also referred to as "parameter estimation".

Community of Practice: A Community of Practice (CoP) is a group of people who share an interest in something, and come together regularly to develop knowledge around this topic, in order to use it in practice (Wenger, 1998).

Conceptual Models: A hypothesis regarding the important factors that govern the behavior of an object or process of interest. This can be an interpretation or working description of the characteristics and dynamics of a physical system.

Corroboration: Quantitative and qualitative methods for evaluating the degree to which a model corresponds to reality.

Deterministic Analysis: This analysis provides a single solution rather than a set of probabilistic outcomes. This type of analysis does not explicitly account for the effects of data uncertainty or variability.

Model: A simplification of reality that is constructed to gain insights into select attributes of a physical, biological, economic, or social system. A formal representation of the behavior of system processes, often in mathematical or statistical terms.

Model Evaluation: The iterative process of determining whether a model and its analytical results are sufficient to agree with known data and to resolve the problem for informed decision making.

Probabilistic Analysis: An analysis that utilizes the entire range of data to develop a probability distribution of the solution (i.e. exposure or risk) rather than a single point value. Probabilistic models are sometimes referred to as statistical or stochastic models.

System: A collection of objects or variables and the relations among them.

Uncertainty Analysis: Investigates the effects of lack of knowledge or potential errors on the model (e.g, the “uncertainty” associated with parameter values or the model framework) and when conducted in combination with sensitivity analysis (see definition) allows a model user to be more informed about the confidence that can be placed in model results.