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An Eye-Opening Approach to Developing and Communicating Integrated Environmental Assessments

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An eye-opening approach to developing and communicating integrated environmental assessments

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Communication among managers, the public, and scientists is the key to successful ecosystem management; however, the varied perspectives and interests of these groups can make such communication difficult. One way to achieve effective communication is to develop a common knowledge base by combining syntheses of key scientific results with information-rich visual elements. Within a management landscape, integrated environmental assessments provide a useful framework for evaluating resources and directing management efforts. The integrated assessment process involves (1) initial investigation, (2) development of a conceptual framework, (3) data navigation, (4) environmental report cards, and (5) science communication. Each step requires the synthesis and visualization of information on the status and trends connected with multiple natural resources. We provide a case study, using examples from selected National Park Service sites in the mid-Atlantic region of the United States. Visual elements (conceptual diagrams, maps, graphs, tables, and photographs) were used to facilitate comparative assessments and to provide a more visual, or "eye-opening", approach to effective environmental decision making.

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Land managers face a variety of challenges, involving threats at different spatial and temporal scales (eg global change, development along management boundaries, pollution from outside protected areas, and introductions of invasive plants, animals, and pathogens). Effective resource management relies upon having and understanding scientific data on the status, trends, and interactions among these elements. Integrated environmental assessments provide a tool for evaluating and redirecting management efforts relative to multiple resources and threats (Grumbine 1994; Christensen *et al.* 1996; Pantus and Dennison 2005; Reagan 2006). A common challenge facing assessment programs is the effective integration, interpretation, and communication of monitoring data among the various stakeholders (Barker 2006). The importance of visual elements in this process cannot be overstated. Conceptual diagrams are a central tenet in science communication and these symbol-based drawings allow ecosystem features and threats to be summarized in self-contained visual representations of key ecosystem processes. These diagrams provide the context (spatial, temporal, and ecological) for informed management decision making. Various environmental indicators can be added to the visualizations, providing the link between ecosystem processes and the ecosystem measures used in the assessment. The conceptual synthesis of processes and threats can also be placed into a model framework, which can be used to test specific hypotheses regarding management actions (Kershner 1997; Harris *et al.* 2003).

In a nutshell:

- The process of developing and communicating an integrated ecosystem assessment creates common ground between multiple stakeholders and is as important as the product itself
- Once the visual elements are accumulated to communicate an integrated assessment, they form a valuable resource for all stakeholders
- Visual elements summarize and synthesize information in a widely understandable format
- Conceptual diagrams ("thought drawings") are powerful tools that link key ecosystem features, environmental indicators, and major threats

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In developing methods for environmental monitoring at National Park Service (NPS) sites in the mid-Atlantic region, we have established a process for interpreting and communicating integrated assessments that is greatly enhanced by visual elements. The process begins with investigations, based on local expertise, followed by the development of a conceptual synthesis, comprising both conceptual diagrams and ecological models, a data navigation system, an environmental report card, and a science communication framework. The initial investigation phase synthesizes current understanding of the system and identifies critical resources, high priority threats, and knowledge gaps. Visual representations of

Figure 1. *Locations of the national parks (red) in the mid-Atlantic region used in the integrated environmental assessment process: (1) Antietam National Battlefield, (2) Catoctin Mountain Park, (3) Chesapeake and Ohio Canal National Historic Park, (4) George Washington Memorial Parkway, (5) Harpers Ferry National Historic Park, (6) Manassas National Battlefield Park, (7) Monocacy National Battlefield, (8) National Capital Parks-East, (9) Prince William Forest Park, (10) Rock Creek Park, and (11) Wolf Trap National Park for the Performing Arts.*

the system can facilitate communication by encouraging resource experts to work toward consensus on the most important ecosystem attributes and on the relationships that need to be included in the diagrams.

All stages of the process benefit from carefully constructed visualizations of thoughts and data, but the combination of graphs, tables, pictures, and diagrams is particularly crucial to the effective communication of analysis results. Visualizations and conceptual diagrams can act as a communal language among scientists, managers, and stakeholders, providing a common knowledge base for further communication. This holistic approach has proven successful in helping diverse stakeholders to prioritize monitoring needs within NPS sites in the National Capital Region.

■ Environmental setting

The NPS is implementing a series of programs designed to provide a stronger scientific basis for its management actions (NPS 1999; Kaiser 2000). The Inventory and Monitoring program was established to fulfill this mission by creating a comprehensive assessment of the status and trends of park natural resources. This initiative involves obtaining the appropriate data, developing ways to analyze this data, and creating mechanisms to communicate the understanding that results from data analysis. This represents a major departure from previous NPS activities and includes a partnership with academia to facilitate the development of an integrated environmental assessment approach. The development of conceptual diagrams is playing a key role in this effort for various NPS sites in the mid-Atlantic, including Antietam National Battlefield, Assateague Island National Seashore, Chesapeake and Ohio Canal National Historical Park, Prince William Forest Park, and Rock Creek Park (Figure 1). These parks represent a spectrum of historic, natural resource, and cultural values. They range widely in size, usage, and surrounding land use. In total, the parks of this region cover over 50 000 ha and span four physiographic provinces: Atlantic Coastal Plain, Piedmont Plateau, Blue Ridge Mountains, and Ridge and Valley. While the area is only 1% of the land managed by the NPS, these parks receive approximately 14% of nationwide NPS visitations (NPS 1999).

All of the parks lie within the rapidly developing Chesapeake Bay watershed and coastal bays of the Atlantic Ocean (Figure 1). Although most of the Chesapeake Bay watershed (more than 90%) remains agricultural or forested (Jaworski *et al.* 1997), the rate of urban growth in the region is among the fastest in the country. Between 1973 and 1996, the rate of urban expansion around Washington, DC, was approximately 22 km^2 per year (Masek *et al.* 2000), and the US Census Bureau reported a 30% increase in population in the counties surrounding the District of Columbia from 2000 to 2003.

The large and increasing population density of the region results in extremely heavy use of the national parks. The George Washington Memorial Parkway alone had over seven million recreational visits in 2004, making it the sixth most-visited park within the National Park Service system (Barna and Gaumer 2005). Many of the management issues in these national parks are related to increasing urbanization. In a regional context, small urban parks act as important refugia in conserving remnants of the natural heritage disappearing from the landscape (Falkner and Stohlgren 1997). Healthy native habitats within densely settled areas also offer considerable social, economic, and educational benefits (Pickett *et al.* 2001). The conceptual diagram process offers a method for infusing these diverse resource values and stressors into discussions of the natural resource management and scientific research conducted in the parks.

■ Initial investigation

The initial investigation phase involves an attempt to capture the current understanding of the system, identify knowledge gaps, and synthesize inputs from various stakeholders, local experts, and managers. This can be accomplished by reviewing available written accounts and soliciting verbal inputs through interviews and/or workshops. It is helpful, at this stage, to identify and ultimately integrate the structural elements (habitats, species, geomorphology) and key processes of the system (limiting factors, disturbance, biogeochemical cycles, physics, threats).

The process of developing first drafts of conceptual diagrams provides a central focus in working toward consensus on the key structural and functional properties of an ecosystem. Conceptual diagrams can help to clarify thinking; words can be ambiguous, but images link to the message being portrayed. They facilitate communication, both one-way (the presentation of the idea) and two-way (idea development). By providing both context and synthesis, the process of developing conceptual diagrams can be used to identify knowledge gaps, priorities, and other essential elements.

■ Conceptual framework

Synthesis of the knowledge gained in the initial investigation of the key elements, the main stressors, and the principal management objectives can be used to develop a conceptual framework. This can be presented in two ways: (1) as conceptual diagrams that are intended to be dynamic and are the primary communication tool among scientists, managers, and stakeholders, and (2) as conceptual models, which can be used to explore specific hypotheses related to the success of management actions (Carruthers *et al.* 2002; Harris *et al.* 2003). This combination of products provides a scalable set of hypotheses regarding the key attributes and threats to urban parks. The integration of conceptual diagrams into the process of model construction helps to synthesize regional issues while also communicating details of system processes. Where data are available, this empirical evidence is captured in the conceptual framework. However, where this is not the case, the diagrams and models capture key ideas and qualitative information in a formalized framework that can later be refined and quantified (Jackson *et al.* 2000).

Figure 2a provides an example of a conceptual diagram created during a workshop of NPS staff (NCRN 2006). The parks of the mid-Atlantic region protect nationally and regionally important water, forest and grassland, wildlife, and cultural and recreational resources. The major threats that these parks face were identified as urban encroachment adjacent to parks (associated with increases in water and air pollution, disease outbreaks, and invasive and pest species), and transportation or utility corridors that pass through parks (associated with interruptions of the natural flow of water and movements of biota). This diagram represents generic park processes throughout the entire network of parks, rather than at a specific geographic location.

Conceptual diagrams use symbols to generate self-explanatory, self-contained figures that represent synthesized concepts and knowledge (IAN 2006). The conceptual diagram for the national parks of the National Capital Region (Figure 2a) acts as a general ecosystem model, depicting the key features and major threats to the region's parks. The diagram was reviewed and refined by regional park managers and represents their broad

Courtesy of J Rundy (NPS) and T Saxby (IAN)

Figure 2. *Generalized National Park conceptual diagrams: (a) highlighting key resources and key threats, and (b) detailing changes in stream processes with urbanization.*

Figure 3. *A conceptual stressor-effect model of the nitrogen cycle from the perspective of National Park streams. Boxes represent sources of nitrogen from adjacent lands (brown), stressor pathways (blue), and standing nitrogen stocks in National Parks (green). Controls on input processes are represented by bow-tie symbols. NAAQS = national ambient air quality standards, BNR = biological nutrient removal, and BMP = best management practice.*

hypotheses regarding the resources and the stressors of concern in relation to their management activities. Diagrams can be nested to capture greater detail for issues or locations needing special attention. One priority issue raised by the managers was the influence of development (specifically impervious surfaces) on the streams and rivers that act as the primary drinking-water supply for the region (Figure 2b).

The information gained during the initial investigation phase can also be used to construct detailed models of specific ecological processes of concern. We followed a formal approach to develop, apply, and test hypotheses concerning park management, using conceptual ecological models (Sutter 1999; Woodward *et al.* 1999). The multi-step method uses a nested set of models to provide an overview of important ecological interactions and to explore in depth the mechanisms for the small subset of ecological processes deemed most critical for protecting natural resources. A generalized model provides a summary of the system, and is useful for facilitating communication among scientists, managers, and the public. More detailed models can then be constructed in response to specific management or research objectives. The objects and relationships in the qualitative models can be translated into quantitative models once data are available and appropriate hypotheses have been identified (Haefner 1996). The role of increased nitrogen loading to these systems has received special attention (Driscoll *et al.* 2003; Groffman *et al.* 2003), and a more detailed qualitative model can be used to explore the mechanisms associated with nitrogen cycling in urban landscapes (Figure 3). This model traces the specific pathways from stressors to putative ecological damage, and can be readily converted to a quantitative framework (eg the arrows in the model can be parameterized using monitoring data). Underlying these facilitated conceptual syntheses is a multi-layered, supportive dataset, which requires careful organization to ensure effective navigation and therefore efficient utilization of the data.

■ Data navigation

Efficient use and dissemination of data are essential to the integrated ecological assessment process. A data navigation system provides a means to access, analyze, and interpret assessment data (Figure 4). The logic pathway may be geographic (place-based), conceptual (theme-based), and/or associated with indicators (attribute-based). This multi-access approach to monitored data, as well as different graphical and spatial syntheses, is intended to assist in database querying through web-based hyperlinking.

Place-based navigation uses spatially-nested, geo-referenced diagrams to define the spatial extent of the ecological process or indicator of interest. In our example, we defined the mid-Atlantic region by physiographic province and subdivided the region into 11 park-based diagrams. Each park model contains a specific suite of indicators and objectives that were defined through investigation and the conceptual framework process. Depending on the maturity of the monitoring program, knowledge of these processes may be observational, based on data, or a summary of published literature. A benefit of place-based navigation is that users (ie park managers) can more easily determine where particular indicators are being monitored within a park, thereby increasing the possibility of bundling related monitoring or research efforts.

Theme-based navigation makes use of conceptual diagrams to represent biological themes. It provides an intuitive link between the data and the thematic overview diagram developed as part of the initial investigation (Figure 2a). An additional data entry point was a series of models constructed to reflect the National Research Council's priority environmental research challenges (biogeochemical cycles, biological diversity, climate variability, hydrologic forecasting, infectious disease, and land-use dynamics; NRC 2001). Unlike place-based diagrams, which define the unique resources of a particular park, theme-based diagrams are used to find commonalities in threats to, or value of, resources. Theme-based diagrams describe broad-scale, complex ecological relationships and are more likely to draw upon data for a suite of indicators (eg air quality) than on any particular attribute.

Attribute-based navigation is based on collecting ecological data, which can ultimately be used for indicator reporting, to assess comparative ecosystem health of parks. The National Park Service's Inventory and Monitoring program has constructed a tiered framework that organizes monitoring indicators ("vital signs") into three levels of specificity (NPS 1999). Data may be accessed at any of these hierarchical levels, depending on the needs of the user. The indicator data are both nested within the attribute-based navigation system and cross-linked to provide synthesis information for specific locations (place-based) or conceptual ideas (theme-based).

■ Environmental report cards

Assessing the health of an ecosystem requires historical and current vital-signs data to be organized, assimilated, and synthesized (Wells 2003). Integrating diverse datasets to allow comparison of health status among estuarine systems has been carried out at large scales (Ferreira 2000; Bricker *et al.* 2003). Here, we present an example from the Maryland Coastal Bays, recognizing that the process can be transferred to the vital-signs indicators used to monitor parks within the National Capital Region. Ecosystem health indicators such as water quality, living resources, and habitat features were used to compare the different bays within the Maryland Coastal Bays region (Figure 5). The ecosystem health indicators were selected because they are responsive to human activities, available to be mapped throughout the coastal region, and variable across the environmental gradients. Three water quality indicators (water quality index, harmful algal blooms, macroalgae), three living resource indicators (benthic index, hard clam abundance, sediment toxicity) and three habitat indicators (seagrass area, wetland area, natural shoreline) were used to rank the ecosystem health in each bay. The nine indicators were equally weighted, so that the resulting ranking integrates the various environmental features. The region was divided by sub-watershed into six regions, and the integrated index compared ecosystem health among the six regions. Overall, the northern bays were ranked as less healthy than the southern bays, reflecting the population density and development patterns of the coastal areas.

After choosing appropriate indicators and determining appropriate spatial and temporal sampling schedules, the next phase involves integrating a number of diverse parameters into a meaningful assessment of ecosystem status for spatial comparison and tracking of trends over time. This can be carried out at a broad scale, for example, among the mid-Atlantic estuaries of the US (Kiddon *et al.* 2003), or can compare different regions within a system (Wazniak *et al.* in press). By choosing appropriate ecosystem indicators, this approach can provide effective synthesis of ecosystem health status and integrity, and is particularly amenable to effective communication among scientists, managers, and the public.

Figure 4. *Example of data-navigation framework intended to disseminate environmental data via an integrated website. Environmental indicators, which are measured and put into a database, can be accessed via three routes: geographic (place-based), conceptual (theme-based), and indicator (attribute-based). The geographic route uses an overall map linked to individual park maps. The conceptual route uses an overall conceptual diagram linked to ecological vignettes. The indicator route uses a hierarchal series of general to specific indicators.*

■ Science communication

Effective science communication is the successful dissemination of knowledge to a wide range of audiences, from specialist scientists through to managers, politicians, and the public (Thomas *et al.* 2006). Integrated assessments need to culminate in the effective communication of findings and recommendations. Many scientists believe that doing excellent science is enough, and that this knowledge will be found and used at the appropriate time. Unfortunately, the public, politicians, and even environmental managers rarely read journal articles or highly specialized books, so these media alone do not constitute effective science communication. Increasingly, scientists are called upon to comment on current environmental problems and the search for solutions; however, they often lack the tools to communicate their knowledge, especially in the face of the uncertainty inherent in the scientific process. With appropriate communication tools, it is possible for scientists to better explain their messages to a broader audience, creating greater understanding, and demystifying both scientific knowledge and the scientific process. Only when effective science communication is achieved will the relevance of science to society in general be recognized.

The key elements of science communication are synthesis and context. Raw data do not provide much insight

***Figure 5**. An environmental report card developed for Maryland's Coastal Bays, including Assateague Island National Seashore, in which water quality, living resources, and habitat indicators were used to rank the sub-watersheds of the coastal bays behind the barrier islands. Modified from Wazniak* et al. *(2004).*

to anyone except perhaps the investigator collecting the data. Rather, data that have been analyzed, interpreted, and synthesized are needed for meaningful science communication to occur. Context allows people to understand why you are measuring what you are measuring, or why you care about a certain issue. The audience must first be able to see the "who, what, where, when, and how" of the data that are used to support the ideas, so that one can then tell them "why". Effective visualization can communicate these facets of the data. A common strategy is not to present the data, but instead to inform the audience that the data are very complicated and that the listeners should just trust the scientist that the ideas are supported by the missing data. This is a flawed strategy, and often indicates that the scientist has not worked hard enough to develop effective communication devices. Making a point with the aid of data visualization is very powerful. The audience needs to be able to see and interpret the data themselves; they can be guided through this process, but they need to know that the data exist.

A variety of visual elements can be invoked to communicate science. Satellite photos and maps provide geographic context and are information-rich. Depending on scale, satellite photos provide extra information by showing topography and land use, as well as water clarity, depth, and movement. Aerial photos can serve as excellent site-scale maps. Experimental photos can depict methods and display visible impacts of experimental manipulation, especially when taken at different times during a study. The use of historical photos can help verify conjecture and anecdotal evidence. Graphs and tables are the most common forms of data presentation; it is, however, essential that they portray a clear, easily interpreted message.

These visual elements can be combined to provide unique information (Figure 6). For example, a combination of a photo and a conceptual diagram can effectively orient the audience to the study site, or explain methodology. Photos and graphs, used together, can help with the visualization of results. Results can be overlaid onto maps, which allow the audience to envisage the overall context. Creating effective graphics can be time-consuming, but appropriate use of illustrations will dramatically improve the communication of science – a picture really is worth a thousand words!

■ Conclusions

Active integration of political, financial, and scientific aspects of ecosystem management is increasingly important as the spatial extent and intensity of human impacts

Figure 6. *An illustration of visual elements of science communication for Rock Creek Park, in which maps are combined with photographs, data, and conceptual diagrams.*

expands (Dennison *et al.* 2004). The effort to collect environmental data is generally resource-intensive, requiring large expenditures of time and money. The subsequent application of data to inform management, stimulate research, and direct monitoring efforts is often not accompanied by adequate integration. Yet, integrated assessments are one of the most important tools in the ecosystem-management toolbox. Timely assessments provide feedback on management actions, so both managers and stakeholder groups can evaluate progress, target restoration, and/or protection efforts.

This work was conducted for the National Park Service, which is legislatively mandated to communicate with a broad audience of interested people having varying degrees of background and understanding concerning ecosystem processes. As such, a multi-phased assessment strategy, which engaged stakeholders early and often, was essential to the development of final products that could be accessed by people both with and without scientific backgrounds. The effective communication of data to diverse audiences should be a goal of all scientific endeavors, especially those requiring large expenditures of public funds.

Visual communication devices can literally open people's eyes and allow individuals to more acutely perceive the world around them. This improved understanding will lead to more informed decision making and better social discourse on various issues. Visual devices work – they can transcend scientific jargon by using images and symbols that provide information and knowledge. Scientists use multivariate datasets; thus, a multimedia presentation of data is warranted. Some data lend themselves to the creation of graphs, or to maps, or to tables.

Finally, the incentive to develop more effective approaches to integrative environmental assessment has never been greater than it is at present. To avoid becoming swamped with meaningless data, just when we most need synthesized analyses for improved environmental management, we need to open our eyes to new ways of communicating data and enhancing our understanding, so as to achieve better stewardship of our natural resources.

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References

Barker S. 2006. Environmental communication in context. *Front Ecol Environ* **4**: 328–29.

Barna D and Gaumer G. 2005. NPS director says visitation to National Parks up in 2004. Washington, DC: Department of Interior, National Park Service.

Bricker SB, Ferreira JG, and Simas T. 2003. An integrated methodology for assessment of estuarine trophic status. *Ecol Model* **169**: 39–60.

Carruthers TJB, Dennison WC, Longstaff BJ, *et al.* 2002. Seagrass habitats of northeastern Australia: models of key processes and controls. *B Mar Sci* **71**: 1153–69.

Christensen NL, Bartuska AM, Brown JH, *et al.* 1996. The report of the Ecological Society of America committee on the scientific basis for ecosystem management. *Ecol Appl*: **6**: 665–91.

Dennison WC, Carruthers TJB, Thomas JE, and Glibert PM. 2004. A comparison of issues and management approaches in Moreton Bay, Australia and Chesapeake Bay, USA. In: Wong MH (Ed). Developments in ecosystems, vol 1. Wetlands ecosystems in Asia: function and management. Amsterdam, Netherlands: Elsevier.

Driscoll C, Whitall D, Aber J, *et al.* 2003. Nitrogen pollution: sources and consequences in the US northeast. *Environ* **45**: 8–21.

Falkner MB and Stohlgren TJ. 1997. Evaluating the contribution of small national park areas to regional biodiversity. *Nat Area J* **17**: 324–30.

Ferreira JG. 2000. Development of an estuarine quality index based on key physical and biogeochemical features. *Ocean Coast Manage* **43**: 99–122.

Groffman PM, Bain DJ, Band LE, *et al.* 2003. Down by the riverside: urban riparian ecology. *Front Ecol Environ* **1**: 315–21.

Grumbine RE. 1994. What is ecosystem management? *Conserv Biol* **8**: 27–38.

Haefner JW. 1996. Modeling biological systems: principles and applications. New York, NY: Chapman & Hall.

Harris, GP, Bigelow SW, Cole JC, *et al.* 2003. The role of models in ecological management. In: Canham CD, Cole JC, and Lauenroth WK (Eds). Models in ecosystem science. Princeton, NJ: Princeton University Press.

IAN (Integration and Application Network). 2006. Symbol libraries. www.ian.umces.edu. Viewed 8 Jun 2007.

Jackson LJ, Trebitz AS, and Cottingham KL. 2000. An introduction to the practice of ecological modeling. *BioScience* **50**: 694–706.

Jaworski NA, Howarth RW, and Hetling LJ. 1997. Atmospheric deposition of nitrogen oxides onto the landscape contributes to coastal eutrophication in the northeast United States. *Environ Sci Technol* **31**: 1995–2004.

Kaiser J. 2000. Bringing science to the national parks. *Science* **288**: 34–37.

Kershner JL. 1997. Monitoring and adaptive management. In: Williams JE, Wood CA, and Dombeck MP (Eds). Watershed restoration principles and practices. Bethesda, MD: American Fisheries Society.

Kiddon JA, Paul JF, Buffam HW, *et al.* 2003. Ecological condition of US mid-Atlantic estuaries 1997–1998. *Mar Poll B* **46**: 1224–44.

Masek JG, Lindsay FE, and Goward SN. 2000. Dynamics of urban growth in the Washington, DC metropolitan area, 1973–1996, from Landsat observations. *Int J Remote Sens* **21**: 3473–86.

NCRN (National Capital Region Network). 2006. A conceptual basis for natural resource monitoring. Washington, DC: Department of Interior, National Park Service. http://ian.umces.edu/ncr/ pdfs/nrm_booklet.pdf. Viewed 8 Jun 2007.

NPS (National Park Service). 1999. Natural resource challenge: the National Park Service's action plan for preserving natural resources. Washington, DC: Department of Interior, National Park Service. http://science.nature.nps.gov/im/monitor.

NRC (National Research Council). 2001. Grand challenges in environmental sciences. Washington, DC: National Academy Press.

Pantus FJ and Dennison WC. 2005. Quantifying and evaluating ecosystem health: a case study from Moreton Bay, Australia. *Env Manage* **36**: 757–71.

Pickett STA, Cadenasso ML, Grove JM, *et al.* 2001. Urban ecological systems: linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. *Annu Rev Ecol Syst* **32**: 127–57.

Reagan DP. 2006. An ecological basis for integrated environmental management. *Hum Ecol Risk Assess* **12**: 819–33

Sutter II GW. 1999. Developing conceptual models for complex ecological risk assessments. *Hum Ecol Risk Assess* **5**: 375–96.

Thomas JE, Saxby TA, Jones AB, *et al.* 2006. Communicating science effectively: a practical handbook for integrating visual elements. London, UK: IWA Publishing.

Wazniak C, Hall M, Cain C, *et al.* 2004. State of the Maryland coastal bays. College Park, MD: Maryland Department of Natural Resources, Maryland Coastal Bays Program, and University of Maryland Center for Environmental Science. http://dnrweb.dnr.state.md.us/pressroom/MCB.pdf. Viewed 8 Jun 2007.

Wazniak CE, Hall MR, Carruthers TJB, *et al.* Linking water quality to living resources in a mid-Atlantic lagoon system, USA. *Ecol Appl.* In press.

Wells PG. 2003. Assessing health of the Bay of Fundy – concepts and framework. *Mar Poll B* **46**: 1059–77.

Woodward A, Jenkins KJ, and Schreiner EG. 1999. The role of ecological theory in long-term ecological monitoring: report on a workshop. *Nat Areas J* **19**: 223–33.

