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Nutrient Loadings to Surface Waters: Chesapeake Bay Case Study

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Nutrient pollution poses the greatest of all recognized threats to Chesapeake Bay.

L. Eugene Cronin, *Baltimore Sun*, March 22, 1967

The thing that really bothers me is that when people like me grow old and die off, there leaves a generation back that has no idea of what the conditions of the river were. They don't have the memory at all about the ten barrels of crabs a day a person could catch . . . about the soft crabs crawlin' in the clear water across grassy bottoms. . . . There's going to be nothing in those computer memory banks . . . that can generate the enthusiasm for the Bay that those sights and sounds did.

Senator Bernie Fowler, *Baltimore Sun*, June 14, 1992

Nutrient inputs that result from human activities often cause aquatic ecosystems to become overloaded with nutrients and deficient in oxygen, a process referred to as cultural eutrophication. This phenomenon occurs when nutrient inputs exceed the ability of the system to absorb and use them—its assimilation capacity—resulting in the degradation of water quality.[1] Since the 1960s, environmental scientists and managers have struggled with the causes, consequences, and prevention of eutrophication. Our analysis is concerned with the relationship between environmental research by the science community and the formulation, implementation, and evaluation of nutrient control strategies by the management community.[2] We will not explicitly treat such important problems as water use, the enforcement of government regulations, or the development of a new social ethic for the public stewardship of natural resources. We ask the question, "How and why does the management community respond (or not respond) to new scientific information on the causes and consequences of nutrient loadings to surface waters?"

Since the flow of information between the research and management communities is neither one way nor linear, we must also be concerned with the response of the research community to the needs of management. The interplay among the research and management communities characteristically involves feedbacks between different levels of government (local, state, and federal), public and private institutions, citizens' groups, and individuals. The complex nature of these interactions and the current compartmentalization of ecology and economics into opposing forces create an inertia that reflects both the bureaucracy within which the research and management communities are imbedded and the multiple ecological, economic, and social interests that management agencies represent.

For this case study, we have selected the Chesapeake Bay. As for most of the nation's coastal ecosystems, nutrient loading to the watersheds of the main Bay and its tributaries (Figure 1) has increased substantially in the decades since World War II, largely as a consequence of rapid population growth and increases in agricultural fertilization, the density of farm animals, and atmospheric inputs. This has been a matter of increasing concern throughout the Chesapeake Bay watershed, especially in the states of Maryland and Virginia, the economies of which are closely tied to the Bay and its resources. Perhaps as a consequence of this and its proximity to Washington, D.C., the Bay has been the subject of much political and scientific attention and controversy since the early 1960s. For these reasons, and because the responsibility for nutrient management resides with individual states, our analysis of the relationship between science and management will focus on the state of Maryland. We hope to show how uncertainty, the availability of cost-effective solutions, and forces inherent to the conduct of the science and management communities have interacted to (1) limit the information exchange critical to the objectives of both communities and (2) inhibit the timely development and implementation of comprehensive nutrient management strategies.

The environmental effects of anthropogenic nutrient[3] enrichment (cultural eutrophication) began to receive national and international attention in the 1960s with major efforts to control nutrient loadings and continued during the 1970s to the present. In the Chesapeake region, the main event

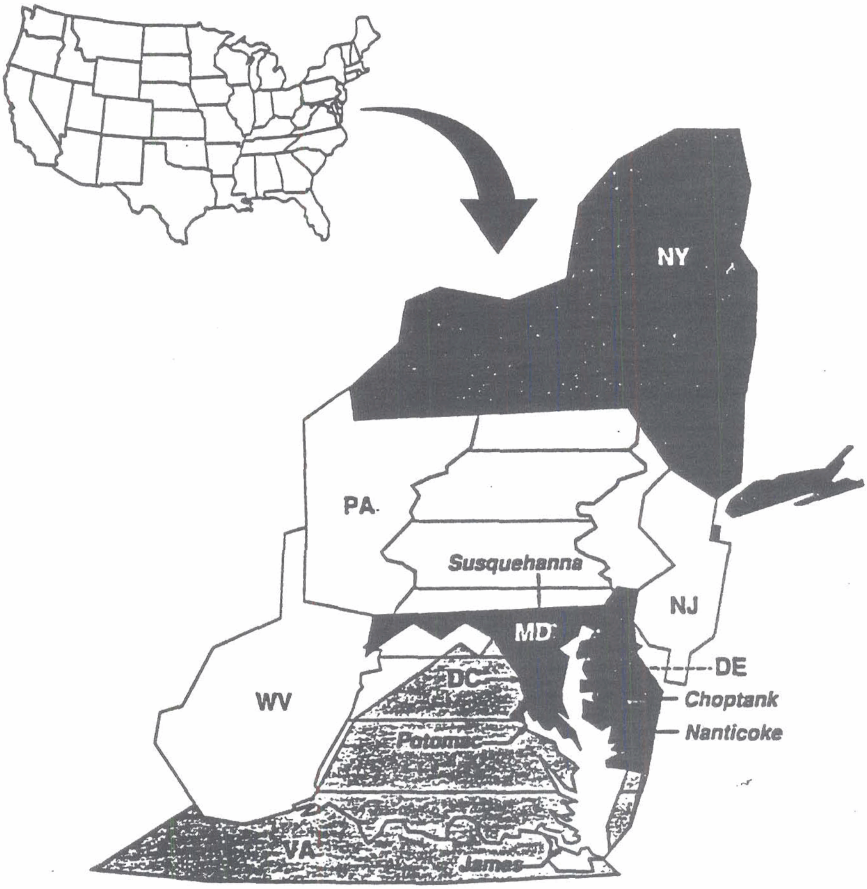

FIGURE 1 Drainage basin of Chesapeake Bay.

during this period was the U.S. Environmental Protection Agency (EPA) Chesapeake Bay Study mandated by Congress in 1976, implemented in 1977, and completed in 1983 with the release of the Chesapeake Bay Program reports: *A Profile of Environmental Change* (EPA, 1983d), *Findings and Recommendations* (EPA, 1983b), and *A Framework for Action* (EPA, 1983c). The implementation of this study and the publicity that surrounded its completion had a major impact on the perspectives of both science and management communities and on the interplay between them, much of which was (and is) modulated by public interest and political pressure. Thus, for the purposes of our analysis, we divide our narrative of the sequence of events into the "formative" years prior to the EPA Bay Study (1965–1977), the period of the EPA Bay Study (1977–1983), and the "action" years following the Bay Study (1983–1992) (see Figure 2).

THE FORMATIVE YEARS

Nationally, the perception of eutrophication as a water quality problem was largely based on studies of the effects of nutrient loading to freshwater systems in which phosphorus (P) is usually the controlling nutrient (American Society of Limnology and Oceanography, 1972; National Research Council, 1969). Vollenweider (1968, 1976) published his widely accepted model of phosphorus limitation in lakes, an empirical analysis that also appeared to be applicable in concept to estuaries where marine and freshwaters mix (Ketchum, 1969). The generality of Vollenweider's model for lake systems was vividly demonstrated through the experimental manipulation of lakes in Canada (Schindler, 1974). Schindler (1977) went on to show that lake communities are able to compensate for deficiencies of nitrogen (N) and carbon through gaseous exchange with the atmosphere, and that attempts to control nitrogen loading may actually degrade water quality because they may result in the growth of noxious blue-green algae (which are capable of fixing nitrogen). In contrast, research in marine systems was beginning to produce evidence that N, not P, is the principal nutrient limiting primary production (Ryther and Dunstan, 1971). However, despite new scientific evidence that N-control would also be necessary (see Boynton et al., 1982; Nixon and Pilson, 1983), nutrient management in the Chesapeake region through the 1970s and into the 1980s was dominated by the growing body of evidence for phosphorus limitation in freshwater systems.

Federal Studies and Legislation

The Water Pollution Control Acts (also known as the Clean Water Acts, CWAs) of 1965 and 1972 reflected a growing concern over the pollution of lakes and rivers and the threat this posed to the nation's water supply, living resources, recreational use, and aesthetics (see Figure 2). The 1965 CWA required the adoption of enforceable ambient water quality standards for all interstate waters. As in the past, the primary responsibility for nutrient management was vested in the states. In the 1972 amendments to the CWA, Congress drastically altered the nation's management approach. It changed the focus from ambient water quality to effluent standards by calling for the nationwide implementation of secondary treatment. Technology-based performance standards became the basis of regulating nutrient (and other contaminant) inputs, and federal funding to the states for the construction and upgrading of sewage treatment plants (STPs) was increased from 55 percent

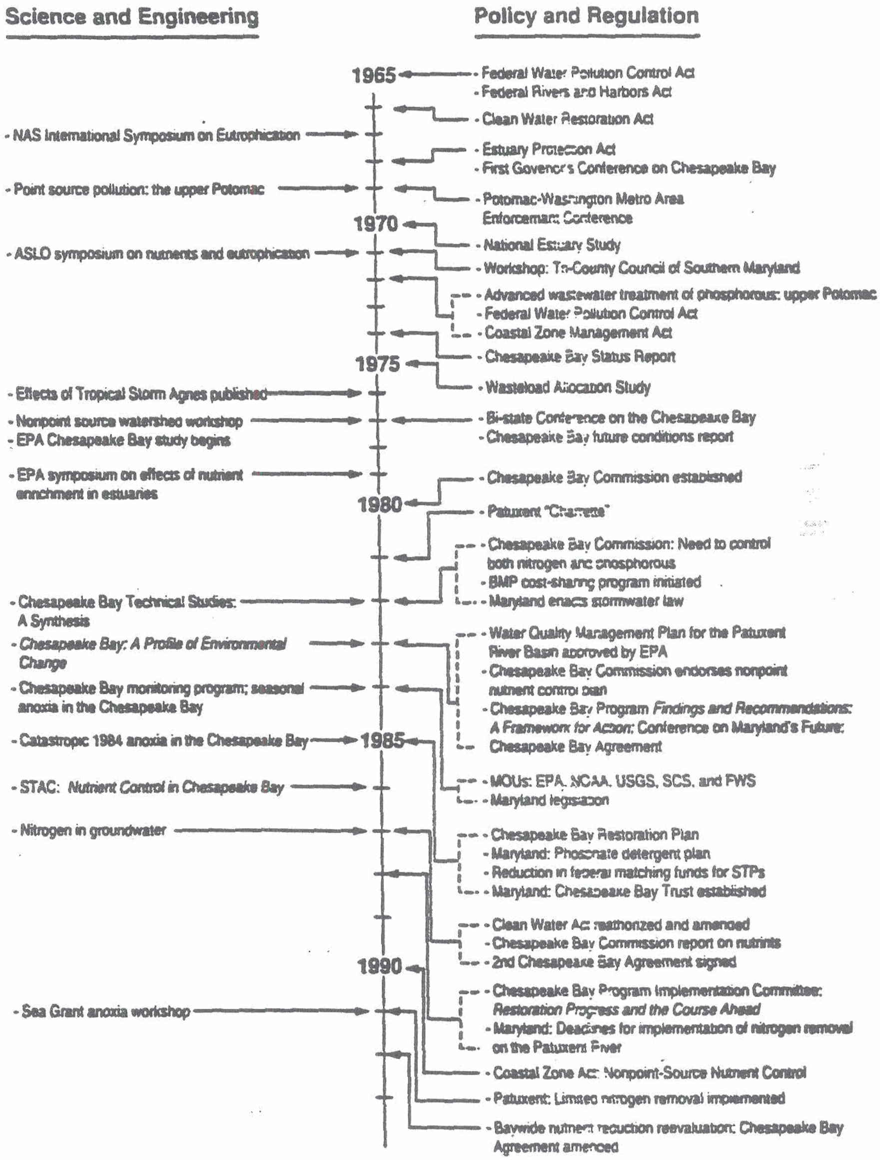

FIGURE 2 Timeline of significant events in the Chesapeake Bay management program.

to 75 percent of capital costs. The act also outlawed all point-source discharges of contaminants and established a permit process for dischargers who could not meet this requirement. This was the National Pollutant Discharge Elimination System (NPDES), which set legal limits on the quantities of contaminants that could be discharged. The 1972 CWA effectively gave the federal government the enforcement power to regulate nutrient inputs to the nation's surface waters. The responsibility for implementation remained with the states, which were mandated to report on water quality within their borders beginning in 1975. Stimulated by the availability of federal funds and guided by the prevailing "wisdom" calling for the control of point-source P inputs, a nationwide effort was set in motion to upgrade all STPs to secondary treatment, with advanced wastewater treatment for removing phosphorus as necessary.

In addition to the CWAs, several studies were initiated by federal legislation during this period. The 1965 Rivers and Harbors Act directed the U.S. Army Corps of Engineers to conduct a comprehensive "study of water utilization and control of the Chesapeake Bay Basin," including water quality control. The 1966 Clean Water Restoration Act directed the Department of the Interior to conduct a study of estuarine pollution nationwide, and the 1968 Estuary Protection Act directed Interior to "study and develop the means to protect, conserve, and restore" the nation's estuaries.

This legislation resulted in four important reports, which laid the foundations for and ultimately led to the EPA Bay Study:

1. In 1969 the Water Pollution Control Administration reported on the adverse effects of nutrient enrichment in the tidal freshwater reaches of the Potomac and Patuxent rivers.

2. In 1970 the Interior Department's national estuarine study, conducted by the Fish and Wildlife Service, recommended that "An all-out cleanup program for the Chesapeake Bay area might serve as a national and even an international demonstration area, showing what can be accomplished by an enlightened public and a responsible Congress."

3. In 1973 the Corps of Engineers released its Chesapeake Bay Status Report in which water quality in the Bay was assessed as good, with local problems limited to the tidal freshwater reaches of some of the Bay's tributaries.

4. In 1977 the Corps presented its *Chesapeake Bay: Future Conditions* report (published in 1978) to the bi-state conference on the Bay. The report acknowledged the *potential* significance of excess nitrogen and phosphorus loading, listed (but did not quantify) major nutrient sources, and suggested that land use and nonpoint sources of nutrients are related.

It is noteworthy that, although the Corps and Interior reports acknowledged the link between land use and nonpoint-source nutrient loadings, the management community would not give control of nonpoint sources serious attention until the late 1980s and early 1990s. This preoccupation with point sources is evident in EPA's 1975 report to Congress, which proclaimed overenrichment from sewage to be a major problem in the nation's estuaries. The Chesapeake Bay was identified as being particularly vulnerable. Under the leadership of Maryland's Senator Charles McC. Mathias, this would cause the Congress in 1976 to direct the EPA to "undertake a comprehensive study of the Bay's resources and water quality, and to identify appropriate management strategies to protect this national resource."

The Chesapeake Region

In the midst of these studies and federal legislation, symptoms of overenrichment were appearing in Chesapeake Bay and its tributaries during the late 1960s and early 1970s. Massive algal blooms, oxygen depletion, and fish kills in the upper Potomac River were gaining the attention of the public and federal government officials in Washington, D.C. Scientists raised the issue of excess nutrient enrichment in general and N loading in particular during the first Governor's Conference on the Chesapeake Bay in 1968 (Jaworski, 1990). Nutrient distributions and historical records dating back to the 1930s indicated a trend toward increasing eutrophication in the upper reaches of the Bay and its tributaries (Carpenter et al., 1969; Heinle et al., 1970). Declines in the abundance of submerged aquatic vegetation (SAV) were documented in the Rhode River estuary (Southwick and Pine, 1975), the upper Patuxent River estuary, and the main Bay (Bayley et al., 1968, 1978). Stevenson and Confer suggested (1978) that these declines might be related to decreased light because of excessive algal growth. Evidence was also accumulating that wastewater inputs to the upper Patuxent River were beginning to cause eutrophication in the lower Patuxent (Flemer et al., 1969). The 1975 Wasteload Allocation Study, conducted by Hydroscience, Inc. under contract to the state of Maryland, concluded that P is the primary nutrient limiting phytoplankton production in the Bay and that the removal of P from sewage wastes is the highest priority for improving water quality. At the same time, research on estuarine circulation highlighted the need for a more systemwide approach to material transport and retention (e.g. Heinle et al., 1970; Pritchard, 1969).

The concerns of federal officials, scientists, and some local officials are clearly documented by the *Baltimore Sun*. For example, U.S. Congressman Carlton Sickles from Maryland claimed that the Bay is polluted "to the point of public danger," and an official of the U.S. Fish and Wildlife Service reported that the Bay "could be dead in five years" (April 23, 1966). The Assistant Secretary of Interior for fish and wildlife concluded that "you can't clean the Bay up, you've got to clean up the watershed" (August 17, 1966). Congressman Rodgers Morton expressed concern that the Bay is getting worse (February 17, 1967), and the founders of the Chesapeake Bay Foundation charged that "ecologically, the whole Bay is in danger" (June 19, 1967). Leading Chesapeake Bay scientists announced that "Nutrient pollution poses the greatest of all recognized threats to Chesapeake Bay" (L. Eugene Cronin, March 22, 1967) and that concerns over thermal pollution from power plants are distracting the science and management communities from the real problem, sewage pollution (Donald Pritchard, July 1, 1970). During this period, a study released by the Baltimore Regional Planning Council concluded that excess N and P inputs from sewage, agriculture, and natural sources were among the Bay's most important pollution problems (November 5, 1968).

In contrast to the perspective of federal officials and reports by local scientists and citizens' groups, state officials in Maryland insisted that the Bay was doing just fine. A representative of the State Board of Natural Resources referred to claims that the Bay is polluted and a public hazard as "irresponsible" (April 23, 1966). The Maryland Department of Chesapeake Bay Affairs issued a statement that "Bay water quality is good and getting better" (June 20, 1969), and Governor Marvin Mandel announced that "water quality rivals that of 25 years ago" (June 25, 1969). As late as 1977, state management officials continued to claim that the Bay was healthy and that, with the exception of a few hot spots, changes in water quality were due to natural climatic cycles (February, 1977. *Baltimore Sun* series, "Chesapeake Still at Bay"). Thus, the governing body responsible for implementing nutrient control plans, the state, was the least receptive to scientific evidence indicating the early stages of baywide eutrophication.

Control of Point Source Nutrient Loading

In the late 1960s, Jaworski et al. (1969, 1972) documented long-term nutrient trends and related changes in the ecology of the upper, fresh reach of the Potomac. For the first time in the Chesapeake region, Jaworski et al. clearly demonstrated a relationship between nitrogen and phosphorus loading from municipal wastewater discharges and deteriorating water quality, and prescribed a program of advanced wastewater treatment to remove N and P, and lower biological oxygen demand (BOD), a measure of nutrient loading. In 1969 the Potomac River-Washington Metropolitan Area Enforcement Conference agreed to set limits on the amounts of P and N that could be discharged into the upper estuary from STPs as well as on BOD levels (Jaworski, 1990). The agreement was achieved in part because the Washington metropolitan area was faced with a ban on new construction if no action was taken and in part because President Johnson, upon signing the 1965 CWA, made restoration of the Potomac a national priority. Jaworski's research provided the scientific basis for action, but the politics of the day provided the leverage. By 1972 the Blue Plains STP, which discharges into the tidal (freshwater) Potomac, had begun construction of an advanced wastewater treatment facility to remove P and lower BOD. Implementation of N removal was delayed, in part because the management community was skeptical of the need and in part because there was no cost-effective technology.

As this chapter in the Potomac episode was drawing to an end, a grass roots confrontation was developing in the Patuxent River watershed. It involved local politicians and scientists on one hand and regulatory agencies of the state and federal governments on the other (Bunker and Hodge, 1982). In 1971 a workshop involving university scientists and the Tri-County Council of Southern Maryland concluded that the water quality of the lower (salty) Patuxent River estuary had declined to unacceptable levels as a consequence of increases in municipal wastewater nutrient loadings to the upper (fresh) Patuxent. Critical to this conclusion was the existence of "baseline" water quality data collected in the 1930s by university scientists. Armed with this information and a commitment to restoring the Patuxent, the Tri-County Council under the leadership of Senator Bernie Fowler appealed to the state for action over the next five years (1972–1976) to no avail. Finally, in 1977, the council filed suit against the EPA to halt the expansion of an upstream STP until an environmental impact statement could be prepared. In 1978 the council again filed suit, this time against both the state and EPA, claiming that the Patuxent River Basin Water Quality Management Plan, which had been approved by EPA, violated 13 of 15 requirements of the 1972 Clean Water Act. The plan advocated P control as the preferred advanced wastewater treatment method for controlling eutrophication of the Patuxent. The council felt that N control was also needed, a position advocated by the Patuxent River Technical Advisory Group (TAG), an ad hoc committee of prominent university scientists.

The U.S. District Court ruled in favor of the Tri-County Council and directed EPA to prepare an environmental impact statement and the state and EPA to prepare a new water quality plan for the basin. As part of this process, the state contracted with HydroQual, Inc. to assess the impact of a set of nutrient control scenarios using a computer model. The model predicted that P removal would be sufficient, a conclusion that the TAG did not agree with. Following an evaluation of the HydroQual model, the TAG concluded in a letter to William Eichbaum (assistant secretary for the newly created Office of Environmental Programs, Maryland Department of Health and Mental Hygiene, February 6, 1981) that, although the model "is at or near the state-of-the-art for water quality modeling," uncertainties associated with the entire modeling process "preclude the use of model projections as the sole foundation for a management decision of this nature."

At this point the state was in a bind. In the absence of an approved nutrient control plan, the federal government was threatening to withdraw funding to build and upgrade STPs on the river. Faced with the loss of millions of dollars, the state sponsored the Patuxent "Charrette" in 1981, a historic conference organized by Mr. Eichbaum. Using a time-constrained, conflict-resolution process to reach a consensus, the stalemate was broken, laying the foundations for the Patuxent River Nutrient Control Plan for controlling both point and nonpoint inputs of N and P. Like the Potomac plan, the Patuxent plan set limits on total N and P loadings to the river as a whole, and, again, economics was an important factor. Unlike the Potomac plan, which was restricted to the tidal freshwater reach of the system and was formulated quickly in response to new scientific information, the Patuxent plan was truly basinwide and took a decade of struggle and confrontation to develop.

Control of Nonpoint Source Nutrient Loading

A major event occurred in June 1972 that would have a delayed but dramatic impact on the subsequent course of nutrient research and management throughout the Chesapeake region. Hurricane Agnes arrived, inundating the watershed with up to 18 inches of rainfall.[4] The watershed as a whole (64,000 square miles) received over 5 inches in less than three days. Agnes served as a "lightning rod," focusing research activities on a number of important questions, including the response of the Bay and its tributaries to nutrient enrichment (Cheaspeake Research Consortium, 1976). (The immense amount of water runoff carried with it large amounts of nutrients from nonpoint sources such as fertilizers and animal wastes.) The storm demonstrated the systemwide susceptibility of the Bay to nutrient enrichment. Major findings included large increases in nutrient levels caused by high runoff and erosion, and the realization that most of the large quantities of nutrients delivered to the Bay are retained within the Bay (rather than being exported to the ocean). Much of the nutrient input entered the sediments and was released during subsequent years, resulting in unusually high phytoplankton production (Boynton et al., 1982). In effect, Agnes brought important environmental issues before the public and primed the science and management communities for what was to become the EPA's Chesapeake Bay Study.

Clark et al. (1973) made an early assessment of nonpoint nutrient inputs in the Chesapeake watershed. They reported that N runoff from agriculture was more than an order of magnitude higher than that from forested areas. These results were reflected in Maryland's 1975 report to EPA (as required by the 1972 CWA), which emphasized point source inputs but also acknowledged that, "The heavy use of fertilizers and manure on the land results in some runoff to the streams." In 1977 the National Science Foundation

(NSF) sponsored a major workshop on watershed research in North America at the Smithsonian Center for Chesapeake Bay Research in Edgewater, Maryland. Results presented at the workshop confirmed that nonpoint N inputs were a major, if not the dominant, term in the N budget of the Bay. Although managers from both state and federal agencies attended the watershed workshop, more than a decade would pass before this reality would begin to be incorporated into a management scheme specifically directed at nutrient control. There was strong resistance by the management community in general, and by agricultural interests (both scientists and managers) in particular, to the idea that farming practices are related to nutrient loading and water quality in the Bay. This resistance was expressed by the Secretary of the Maryland Department of Natural Resources (DNR), James B. Coulter, who in referring to nonpoint nutrient sources, was quoted as stating that, "There is more alarm than is necessary: it can be controlled with just good housekeeping and old fashioned general sanitation" (*Baltimore Sun*, February 7, 1977).

Unfortunately, this "common sense" approach relied heavily on best management practices (BMP), which were intended primarily to minimize the loss of soil and thereby increase or sustain agricultural productivity. Because most P enters the estuary attached to particles, one by-product of this strategy has been to reduce nonpoint inputs of P. Despite earlier warnings (Walter et al., 1979) and information on loading rates (Jaworski, 1981) that indicated that BMPs derived from soil conservation would have little impact on dissolved nutrients such as N, management planning continued to stress problems of erosion, with little consideration for nutrient control per se. The significance of this was highlighted by studies in the Choptank River basin (on the eastern shore of the Bay), which indicated that nonpoint sources account for about 80 percent of N and 60 percent of P inputs (Lomax and Stevenson, 1981). The emphasis on point-source nutrient control would not begin to change until after the release of the results and conclusions from the Bay Study in 1982 and 1983.

The fact that the Bay is imbedded in a large watershed (about 28 units of land area for each unit of Bay surface area), which was being rapidly modified by human activities, was not generally a part of management or scientific thinking at the time. Management was focused on point-source discharges, and funding for research tended to focus the science community on the effects of sewage and thermal discharges. The problems of overenrichment were thought to be restricted to a few local tributaries such as the upper Potomac and Patuxent River estuaries, where point-source inputs were clearly related to the degradation of water quality. Despite the effects of Tropical Storm Agnes and subsequent research findings, the baywide impacts of nonpoint nutrient loading were not broadly appreciated at this time. Agnes planted the seeds, but serious attempts to understand and control nonpoint sources would await the completion of the EPA Bay Study, the development of a comprehensive watershed (multistate) approach, and the results of research in the 1980s that would document the links between agricultural practices and nutrient loading.

THE PERIOD OF THE EPA BAY STUDY

Setting the Stage

Largely in response to baywide declines in the abundance and harvest of living resources (e.g., submerged aquatic vegetation [SAV], oysters, and shad), Congress in 1976 directed the EPA to conduct a comprehensive, systemwide study of the resources and water quality of Chesapeake Bay and to recommend management plans to protect and restore this national resource. At the same time, the Chesapeake Research Consortium (CRC, formed in 1974 to facilitate a coordinated, baywide research effort) had begun planning for a Maryland-Virginia, bi-state conference on the Bay. Stimulated in part by the *Chesapeake Bay Existing Conditions Report*, released by the Corps of Engineers in 1973, and the Corps's 1977 *Future Conditions Report* (presented at the conference), leading scientists and managers met to discuss the major environmental issues of the day. Secretary Coulter opened the 1977 conference by describing the Chesapeake Bay as "a beautiful, productive body of water that provides a satisfying livelihood to many persons and boundless pleasure to many others." He went on to caution the scientific community that "if, in our zeal to sell a program or carry a point of view we place in the public's mind a picture of a dirty Bay, a Bay that is a threat to the health of fish and man alike, we will do great and needless harm."

It was in this context that leading scientists discussed the Bay environment and concluded that anthropogenic nutrient inputs were the most serious threat to the health of the Bay and acknowledged once again the importance of nonpoint nutrient inputs. Consensus among scientists and managers could only be reached on two broad issues. First, the underlying causes of declines in living resources were uncertain; and second, there was a need for a single government entity to oversee the restoration of the Bay.

In 1977, drawing to a great extent on recommendations of the bi-state conference, the EPA initiated a five-year study emphasizing the problems of nutrient enrichment, toxic substances, and the decline of SAV. As part of this study, the EPA funded CRC in 1979 to organize an international symposium on the *effects of nutrient enrichment in estuaries* (Neilson and Cronin, 1981). Research presented at the symposium highlighted the causes and consequences of nutrient loading in estuaries. Of particular significance for the Chesapeake Bay was the presentation of the first good estimates of total nutrient loads to the Bay, which showed the quantitative importance of nonpoint sources (Jaworski, 1981). When considered in the context of the NSF-sponsored workshop on watersheds two years before, the results of this symposium sent a strong signal that nonpoint sources of nutrients would have to be considered as part of nutrient management plans.

Recognizing the need for interstate, basinwide planning, joint legislation by the Maryland and Virginia general assemblies created the Chesapeake Bay Commission in 1980 to coordinate management activities and advise the legislators of both states. In 1982 the commission acknowledged the need to control both N and P inputs. It worked to formulate, and secure support for, legislation that in 1984 would facilitate the implementation of a broad range of nutrient management actions. In 1983 the commission also recognized the need for a watershed approach when it endorsed the Patuxent River Basin plan as a model for a comprehensive nutrient control strategy that would address the control of both point and nonpoint loadings in terms of total inputs. In the years following the completion of the Bay Study, the commission continued to be an important forum for promoting and guiding legislative actions, as well as the 1983, 1987, and 1992 Bay Agreements.

The Bay Study

The EPA Bay Study involved some 50 research projects, the results of which are summarized in *Chesapeake Bay Technical Studies: A Synthesis* (EPA, 1982) and in *Chesapeake Bay: A Profile of Environmental Change* (EPA, 1983d). These reports supported earlier speculation that water quality was deteriorating, that many living resources were declining, and that these changes were related in some way to land use in the drainage basin. The reports presented evidence based on data collected between 1950 and 1980, that nutrient and chlorophyll concentrations were increasing and that these increases might be related to the baywide decline in SAV and to summer oxygen depletion in the main Bay. It was suggested that declines in fisheries might be related to deteriorating water quality, especially in the upper and midbay and in the upper reaches of the western tributaries. A baywide analysis of nutrient inputs also confirmed the importance of nonpoint sources, which were estimated at the time to supply about 65 percent of P and 80 percent of N inputs. The widespread decline in the abundance of SAV in the Bay, initially described by Stevenson and Confer (1978) and confirmed by Orth and Moore (1983), was shown to be primarily a consequence of nutrient enrichment (Kemp et al., 1983; Twilley et al., 1985). Results from the Bay Study suggested that the whole Bay was changing and that many of these changes were related to increases in nutrient inputs from municipal wastes and agricultural runoff.

Results from the SAV component of the study contributed more to the understanding of the consequences of nutrient enrichment than did the nutrient enrichment component itself. Overall, little new information was generated that would further a mechanistic understanding of the causes and consequences of point- and nonpoint-source nutrient loadings. Trends in water quality parameters were not statistically well documented and advances in the understanding of underlying causes of eutrophication were limited. With the notable exception of the nutrient-SAV work, little was learned that would allow a cause-effect, quantitative analysis of the relationships between nutrient inputs, water quality, and living resources in the main Bay. In a qualitative way, these links made sense, but the scientific evidence needed to make the case remained weak.

With the publication of *Chesapeake Bay: A Framework for Action* in 1983, the EPA presented its recommendations for a range of actions to restore the Bay. Despite the lack of scientific information needed to quantify the effects of anthropogenic nutrient inputs, the major focus of these recommendations was on the control and monitoring of nutrients "to reduce point and nonpoint source nutrient loadings to attain nutrient and dissolved oxygen concentrations necessary to support the living resources of the Bay."

Following the release of this report, the Citizen's Program for the Chesapeake Bay (precursor of the Alliance for the Chesapeake Bay) organized a conference, "Choices for the Chesapeake: An Action Agenda," which laid the foundation for the subsequent signing of the 1983 Chesapeake Bay Agreement by the governors of Maryland, Virginia, and Pennsylvania, the mayor of the District of Columbia, the administrator of the EPA, and the chairman of the Chesapeake Bay Commission. This historic agreement committed the EPA and the states "to improve and protect the water quality and living resources of the Bay system, to accommodate growth in an environmentally sound manner, to ensure a continuing process of public participation, and to facilitate regional cooperation in the management of the Bay." An administrative structure was created to achieve these goals. It consisted of the Chesapeake Executive Council (the appropriate cabinet designees of the governors, the mayor of the District of Columbia, and the regional administrator of EPA), a Citizens Advisory Committee, a Science and Technical Advisory Committee, and an Implementation Committee. For the first time, the states and EPA officially admitted that systemwide problems existed and that they were getting worse, not better, under existing management practices. The momentum created by the 1983 Bay Agreement led to a flurry of legislative actions in 1984, the establishment of the Chesapeake Bay monitoring program, and an unprecedented decade of nutrient-related studies by the science community.

Public participation was an essential ingredient that helped to sustain the high level of environmental activity and facilitated a somewhat reluctant interaction among scientists and managers following the 1983 Bay Agreement. The Alliance for the Chesapeake Bay, which staffs the Citizens Advisory Committee to the Chesapeake Program, was formed to work toward the restoration of the Bay through public education, dissemination of information (e.g., the *Bay Journal*), and citizen involvement. Environmental advocacy groups grew rapidly in membership and influence. The Chesapeake Bay Foundation (CBF), with its motto of "Save the Bay" and a fund-raising pitch that typically begins with "the Bay is dying," increased its membership from about 10,000 in 1983 to more than 80,000 in 1992, making it the largest regional, nonprofit environmental organization in the nation. This allowed CBF to mobilize public opinion and apply pressure on the government to continue the course established by the Bay Study and subsequent agreements.

THE ACTION YEARS

For many, 1984 was considered to be the year of the Bay. At the federal level, EPA, the National Oceanic and Atmospheric Administration (NOAA), the Geological Survey, Soil Conservation Service, and the Fish and Wildlife Service signed memoranda of understanding to coordinate research and management activities related to environmental issues. No single issue preoccupied the Chesapeake Bay's environmental agenda during the 1980s and early 1990s more than the effects of excessive nutrient inputs from point and nonpoint sources. This was reflected in the level of legislative activity in 1984 and 1985, the 1987 and 1992 Chesapeake Bay Agreements, and continuing debates between and within the management and science communities concerning issues such as the need to control both N and P inputs, methods for controlling nonpoint sources of N, and the need for baywide versus basin-specific nutrient control strategies.

Among the most important legislative acts of the 1984 session of the Maryland Assembly was the appropriation of funds for a comprehensive water quality monitoring program. Responding to recommendations in *Chesapeake Bay: A Framework for Action*, EPA (1983c) and the state of Maryland established the most comprehensive water quality monitoring program ever to be implemented in an estuarine system. The Chesapeake Bay Monitoring Program addressed a major problem encountered during the years of the Bay Study—the inability to document how the Bay had changed. Temporal and spatial variability would be monitored in order to determine long-term trends in water quality and living resources, to resolve natural cycles and anthropogenic sources of variability, and to evaluate the efficacy of pollution control programs.

Nutrient Research

The Bay Study spawned an unprecedented research effort during the 1980s, which focused on five key issues: (1) the significance of the benthos (i.e., the bottom of the Bay) in the nutrient dynamics of the Bay, (2) the relative importance of nitrogen and phosphorus in limiting phytoplankton production, (3) quantification of SAV responses to changes in N and P concentrations in the Bay, (4) the causes and consequences of nutrient loading in terms of oxygen depletion (habitat loss) and its impact on living resources, and (5) the significance of and methods for controlling nonpoint-source nitrogen inputs. Research on nutrient fluxes from the benthos demonstrated the role of benthic-water column interactions in controlling the nutrient dynamics in shallow estuaries (Boynton et al., 1980; Kemp and Boynton, 1984). The work of Officer et al. (1984) and Seliger et al. (1985) highlighted seasonal depletion of dissolved oxygen as a measure of the Bay's capacity to support living resources and of climatic variability in controlling the Bay's response to nutrient inputs. Nutrient enrichment studies (e.g., D'Elia, 1987; D'Elia et al., 1986) provided the basis for a report released by the Scientific and Technical Advisory Committee of the Chesapeake Bay Program in 1986 presenting clear and compelling scientific evidence that both P and N removal would be required to improve water quality in the Bay and its tributaries. The report emphasized the fact that cost-efficient technologies are now available for the combined removal of P and N, and reducing BOD, and strongly recommended that N removal be implemented.

Multidisciplinary research on the Bay during the 1980s led to a 1991 workshop sponsored by the Maryland and Virginia Sea Grant College Programs and to the release of a report in 1992 entitled *Dissolved Oxygen in the Chesapeake Bay: A Scientific Consensus.* Based on a comprehensive analysis of oxygen dynamics in the main Bay (Smith et al., 1992), the report emphasized the susceptibility of the Bay to seasonal oxygen depletion and to climatic variability, and concluded that nonpoint nutrient inputs were the primary sources of the nutrients that fueled oxygen depletion in the main Bay. The report also endorsed the goal of achieving at least a 40 percent reduction in nutrient inputs to the Bay and underscored how little is known concerning the relationship between water quality and the capacity of the Bay to support living resources.

In the same year, the results of statistical analyses of monitoring data from the main Bay for 1984–1990 showed a significant decline in total phosphorus (19 percent), a small but significant rise in total nitrogen (2 percent), and no significant trend in oxygen depletion in bottom water (EPA, 1992). The decline in P apparently reflects the effectiveness of point-source controls (enhanced P removal by STPs and the phosphate ban enacted by the Maryland General Assembly in 1985). The relatively small change in total nitrogen levels suggests that the achievement of a 40 percent reduction in N input will depend on the success of nonpoint source controls of N, a conclusion that is consistent with results from the Choptank River where nonpoint sources dominate nutrient inputs and the concentrations of N and phytoplankton biomass increased from 1985 to 1991 (Stevenson et al., 1993). In addition, research on the movement of N through the watershed demonstrated that the major route of N loss from agriculture systems occurs through groundwater (Staver et al., 1987), indicating that effective control of N inputs to the Bay must address subsurface water movements (Staver et al., 1989).

Nutrient Management

Activity in the management arena was also stimulated by the Bay Study. In 1984 the Maryland General Assembly enacted eight authorization and assistance bills that contributed to the management of nutrient inputs to the Bay. Bills aimed at point source management included (1) the State Financial Assistance Program, which created a water pollution control fund and established policy and procedures for using these funds to assist local governments in constructing STPs and implementing stormwater management programs (and to encourage farmers to implement BMPs); (2) the Water Quality Loan and (3) Existing Loan Authorizations bills, which provided bond authorization and increases in the state's share of STP construction costs (in anticipation of reductions in federal funding from 75 to 55 percent) so that the cost to local governments would remain at 12.5 percent; and (4) the Water Pollution Control bill, which provided the authority to require and enforce pretreatment of industrial wastes. Additional funding for the Bay restoration effort was made possible in 1985 when the Maryland Assembly created the Chesapeake Bay Trust to support private and corporate involvement through private donations.

Despite the cumulative evidence that N removal was needed to improve water quality (from the Patuxent Charrette in 1981 to the 1986 STAC report and the 1987 Chesapeake Bay Agreement), resistance within the management community to implementing the measures needed to reduce N inputs remained strong through most of the 1980s. With respect to point sources, management officials in Maryland as late as 1983 held the point of view that nitrogen removal in "all treatment plants in the State that discharge" to the Chesapeake Bay should "never" be required (memoranda from technical and permit staff to the director of the Maryland Water Management Administration dated May 30 and July 20, 1983). Ultimately, as a consequence of inaction by EPA and the Maryland Department of the Environment, the Maryland Assembly passed a bill in 1988 requiring by 1991 the implementation of advanced wastewater treatment to remove N in STPs discharging into the Patuxent.

Legislative action in 1984 also addressed the problem of nonpoint nutrient inputs. The cornerstone of this legislation was the Critical Areas Protection bill, which established a framework for managing shoreline development to minimize erosion and nonpoint-source nutrient inputs as well as for protecting critical habitats within 1,000 feet of the shore. In addition, the Sediment Control bill placed sediment control under the authority of the state; the Drainage of Agriculture Lands bill required the secretaries of Agriculture, Natural Resources, and Health and Mental Hygiene to promulgate regulations for the efficient design, construction, operation, and maintenance of agricultural drainage projects; and the Shoreline Improvement Loan bill authorized funds for projects to reduce shoreline erosion within the critical area. It should be emphasized that the implementation of measures to reduce nonpoint nutrient inputs was, and still is, a voluntary process facilitated by federal and state cost-sharing programs. Furthermore, as these actions suggest, the management of nonpoint source nutrient inputs remained dominated by the notion that soil conservation and nutrient control were synonymous, a perception that would continue through the 1980s.

Although specific actions to control nonpoint nutrient sources would not be forthcoming until the 1990s, the results of the Bay Study and continued research on nutrient runoff from agricultural lands were gaining the attention of the management community. The Chesapeake Restoration Plan, released by the Chesapeake Bay Commission in 1985, recognized the need for basin-specific nutrient control strategies and outlined implementation plans for reducing point and nonpoint nutrient inputs. These included recommendations for a ban on the use of phosphates in detergents (enacted in 1985), improved wastewater treatment throughout the state, reductions in combined sewer overflows, and the development of BMPs to reduce surface nutrient runoff (e.g., planting "buffer strips" in critical areas). The Chesapeake Bay Commission also endorsed the development and use of mathematical models to evaluate the success of nutrient control strategies "before changes can be detected physically," emphasized the importance of nonpoint sources, recommended continued research on the role of N in the Bay ecosystem, and acknowledged the publication of *Statewide Priority Watersheds for the Potential Release of Agricultural Nonpoint Phosphorus and Nitrogen* by the Maryland State Soil Conservation Committee (EPA, 1985). The latter marks an important step toward nonpoint-source nutrient control by ranking all watershed segments based on their potential for nonpoint nutrient discharge to the Bay and its tributaries.

The first significant changes to the CWA since 1972 were made in 1987. These included a change in emphasis from point to nonpoint source controls and a phaseout of construction grants for STPs by 1994 (which had provided nearly $50 billion to states for STP construction from 1972 to 1987). This shifted the burden of funding to the states and increased their authority to control toxic pollutant discharges and nonpoint sources of pollution. With the signing of the 1987 Chesapeake Bay Agreement, broad goals and priorities were established for the restoration and protection of living resources and water quality. Although the agreement contains objectives and commitments for living resources, water quality, population growth and development, public information, education and participation, public access, and governance, the centerpiece was the achievement of a 40 percent reduction in total loads of N and P to the Bay by the year 2000. This was a landmark agreement in that it established a specific and quantifiable goal that was to be reevaluated in 1991 based on the results of the monitoring program and simulation modeling.

For the first time, the agriculture community was forced to confront the question of how to reduce nonpoint source inputs from farms. With the release of *A Commitment Renewed: Restoration Progress and the Course Ahead* by the Chesapeake Bay Program Implementation Committee (EPA, 1988), it was also acknowledged that controlling the input of N would be difficult because nitrogen moves with water, in contrast to phosphorus, which moves with sediment. Finally, Maryland's Coastal Zone Management Plan (approved in 1978 and administered by the DNR), which did not explicitly address the problem of eutrophication, was modified in 1990 to include provisions for nonpoint-source nutrient control and water quality management consistent with the CWA.

The U.S. EPA Chesapeake Bay Program released its *Progress Report of the Baywide Nutrient Reduction Reevaluation* in 1992. The report presents the most accurate estimates to date of nutrient sources and loads. Results of the watershed model reaffirmed the significance of basinwide nonpoint sources (77 percent and 66 percent of N and P inputs, respectively), reinforcing the conclusion that nonpoint source N inputs must be controlled if a 40 percent reduction in inputs is to be achieved. Direct atmospheric deposition of N and P to the Bay and its tributaries was found to be relatively small, but estimates of basinwide inputs suggested that atmospheric deposition could account for as much as 35–40 percent of the total nitrogen input, a conclusion that is consistent with the findings of Fisher and Oppenheimer (1991) of the Environmental Defense Fund. Results of computer computations (using the so-called 3-D model, a three-dimensional, time-variable numerical model) suggest that 40 percent reductions in controllable nitrogen (about 20 percent of total input) and phosphorus (about 30 percent of total input) loads will increase bottom water oxygen levels by 15 to 25 percent. Based on these results and interpretations, the 1992 amendments to the Chesapeake Bay Agreement reaffirmed the commitment to a 40 percent reduction in N and P loadings by the year 2000, placed caps on these loading levels once achieved, specified basin-specific nutrient loads, and called for implementation of nutrient control strategies to achieve these loads beginning in 1993. The 1992 agreement also stipulated that the abundance and distribution of a living resource, SAV, would be used to measure the success of this nutrient control strategy.

The management of nonpoint sources of nutrients remains controversial. Although the 1992 Bay Agreement calls for reductions in atmospheric and agricultural sources of nitrogen, it is unclear how such reductions would be achieved. Both regional and nationwide reductions in nitrogen oxide emissions will be required to control atmospheric deposition. As for agricultural inputs, traditional approaches that rely on expanded implementation of BMPs (designed to reduce surface runoff and soil erosion) are unlikely to have the desired impact on N loading. The management community has interpreted recent results of watershed models and related cost-benefit analyses as indicating that the most cost-effective approaches to reducing nonpoint agricultural inputs are the control of fertilizer applications and animal waste inputs (EPA, 1992). However, the watershed model has been widely criticized as inadequate, and the quantitative effects of tuning fertilizer applications to agriculture production and avoiding accumulations of animal wastes are promising but uncertain. To the extent that groundwater pathways account for most of the nonpoint loading of N, additional measures (e.g., cover crops) that limit the movement of N into groundwater will be required.

DISCUSSION AND CONCLUSIONS

The Interplay Between Science and Management

Our analysis reveals a change in the relationship between science and management as the emphasis in nutrient control shifted from point to nonpoint sources. During the formative years, neither the science nor the management communities in Maryland perceived nutrient enrichment to be an immediate, high-priority problem (compared with thermal pollution, dredging, and the threat of oil spills). Research and management activities tended to focus on local issues and problems, a pattern that may have been reinforced by prevailing climatic conditions. Initial concerns with point source nutrient inputs coincided with a period (1962–1969) of unusually low rainfall when the problems of nutrient enrichment in lakes were first gaining national and international attention. Low rainfall and freshwater runoff have the effect of minimizing nonpoint inputs and maximizing the effects of point source inputs, which are independent of freshwater runoff for the most part. Point source nutrient inputs were targeted and the state implemented secondary treatment by constructing and upgrading STPs. These actions were driven by the federal CWAs, which provided financial incentives, and by public and political pressures precipitated by local water quality problems that did not require sophisticated tools of science to uncover. The relationship between point source inputs and water quality (as indicated by such phenomena as red tides, noxious odors, and fish kills) was usually obvious, and it was generally assumed that nutrient loading could be managed through secondary treatment to control point source loadings. Management moved out in front of the science and formulated their own "best guess" scenarios as to the degree and kinds of nutrient reductions needed to improve water quality.

The Potomac case may be considered an exception in this regard. Scientific research preceded management action, which appeared to be closely coupled to new scientific information establishing quantitative relationships between nutrient loading and water quality. Low rainfall during the 1960s undoubtedly exacerbated conditions in the Potomac River where noxious algal blooms, fish kills, and generally unsanitary conditions were occurring at the doorstep of the White House. Here, secondary treatment and advanced wastewater treatment for P reversed the trend of declining water quality, at least in the tidal freshwater reach of the estuary (Jaworski, 1990).[5] However, the Potomac case was unique, not only in terms of the apparent close coupling between new scientific information and management action (which probably reflected the river's proximity to Washington, D.C., and its role as a political showcase as much as anything else), but also in terms of the massive expenditure of federal funds (about $1 billion) and its limited impact on research and management in the greater Chesapeake Bay region.

A fundamental change in the relationship between science and management began to emerge with the controversy over N control in the Patuxent River basin. The spatial displacement between the upstream location of point source nutrient inputs and downstream effects not only set the stage for a decade-long debate over the control of N and nonpoint source inputs, it marked the beginning of a systemwide approach to the problem of eutrophication in the Bay and its tributaries. With this seed, the connection between nutrient loading and water quality in the Bay as a whole began to crystalize when research sponsored by the EPA Bay Program related widespread decline of SAV to overenrichment. At this point, science began to move out in front of management, in part because of the complex nature of the problem and in part because of the lack of funding (including financial incentives from the federal government) to develop and implement new approaches and technologies required to address the problems of N and controlling nonpoint source inputs.

The management community as a whole did not acknowledge the need to control N and nonpoint source inputs until the late 1980s when the cumulative impact of evidence from environmental research became overwhelming. With each iteration of nutrient inventories and budgets, the predominance of nonpoint sources became unequivocal. The shift from P to N limitation along the transition from fresh to salt water areas was clearly demonstrated. Studies of benthic nutrient fluxes revealed that models of water quality in the Bay would have to incorporate benthic-water column interactions into their calculations; large-scale baywide studies revealed the mechanisms by which nutrient inputs cause oxygen depletion in the main Bay, and showed that nonpoint sources were the principal cause; and current soil conservation practices were shown to have little effect on N input to the Bay. These advances could not have been made without a major research and monitoring effort by the science and management communities in the Chesapeake Bay region. Rather than depending on science information generated by research in Canadian and European lakes, the management process was increasingly guided by new scientific information on the Bay itself, information that currently influences nutrient management in estuarine systems worldwide.

Explicit actions to control N loading have been limited to point source discharges to the upper Potomac and Patuxent rivers, and strategies that target nonpoint sources of N are only now being seriously considered. On the receiving end, the 1992 Bay Agreement identifies the return of SAV as an initial measure of the effectiveness of nutrient management in the restoration of living resources and water quality. Long lags (on the order of 10 years or more) between scientific discovery and management action are a common feature of each of these cases. To some extent, this reflects a considered and informed decision-making process related to social and economic considerations and to the uncertainty of environmental science. However, the record also suggests that this is often not the case, in part because sufficient information is simply not available (increasing the uncertainty), but also because of ineffective information exchange between the science and management communities. Consequently, delays in the use of new scientific information are often related more to politics and economics (compare the histories of point source nutrient control in the Potomac and Patuxent cases) than to the quantity and quality of available information. As clearly stated by Ian Morris, the director of the Center for Environmental and Estuarine Studies of the University of Maryland (*Baltimore Sun*, July 17, 1983), "There is nothing wrong with forging ahead before knowledge of a problem is complete [because] it never is—but you need to keep close touch with good scientific study, and that close touch is being lost." A comparative study of coastal seas management in different regions from the Baltic Sea to the Inland Sea of Japan clearly shows the importance of "independent but relevant science" to the decision-making process (Morris and Bell, 1988). This study suggests that, although new scientific information rarely initiates management action, the availability of good information and scientific advice not only enhances the responsiveness and quality of management actions but also often reinforces management decisions and helps keep the management process on track.

Sources of Inertia

Inertia in the management process occurs for a variety of reasons that range from the sheer magnitude of the problem and the cost of solving it to poor problem definition, uncertainties inherent in the prediction of ecosystem behavior, and polarization between the science and management communities. Two features of the Chesapeake Bay experience that exemplify magnitude and cost stand out: the need for more STPs with advanced wastewater treatment and the need to control nonpoint sources. Clearly, reliance on a particular technology (secondary treatment) as the basis for regulating nutrient inputs has inhibited the development of alternative (less costly, more effective?) approaches and technologies (see Officer and Ryther, 1977). Furthermore, as the fiscal realities of advanced wastewater treatment for P removal became apparent in the 1970s, the Congress and the General Accounting Office became alarmed and instituted a federal "Advanced Wastewater Treatment Policy," which essentially subjected STPs contemplating advanced P or N removal to extreme scrutiny. The effect was to create a powerful disincentive for advanced wastewater treatment, especially for N. Consequently, STPs on the Patuxent did not begin to remove nitrogen until 1991, several years after cost-effective technology became available, a decade after the Patuxent Charrette, and more than two decades after scientists first began to worry about N loading to the Bay.

In the case of nonpoint sources, their diffuse nature and relationship to patterns of landuse catapulted the problem of nutrient regulation to a new level involving not only water quality and living resources but also socioeconomic forces related to population growth in the watershed. Implementation of point source controls has little direct impact on the social fabric of the population, and the costs of reducing point source inputs can be predicted with a relatively high degree of certainty based on knowledge of loading rates and the required technology. This is not the case for nonpoint inputs. Management of nonpoint sources inevitably leads to conflicts between prevailing patterns of land use (by farmers, homeowners, industry, government, etc.) and the implementation of nutrient control schemes. The cost of reducing nonpoint sources is more unpredictable because of uncertainties in loading rates and in the effectiveness of different methods of nutrient control. Thus, for justifying the social and economic costs of nutrient management, it becomes much more important to demonstrate cause-effect relationships between nonpoint sources, water quality, and the capacity of the ecosystem to support living resources. Decision makers insist on more information before implementing control measures.

Scientists and managers typically function on different time scales, resulting in tension and distrust between the two groups, which in turn inhibits effective exchange of information and consensus on problems and their solution. For the most part, environmental scientists are cast in the role of conducting research intended to further our understanding of nature. Advances occur on time scales that are dictated by factors ranging from the peer review process to the variability that characterizes populations of organisms, the ecosystems within which they function, and the climatic factors that perturb them. In contrast, managers are expected to make informed decisions and solve problems in a "timely" fashion and are often under considerable pressure to do so on political time scales that are short relative to the generation of new scientific understanding. To compound the problem, success in the science community is achieved through a process that emphasizes peer review, so there is little motivation to communicate outside the science community (except when funds are needed for research). Within the management community, success is measured, in part, by the outcome of the decision, which typically must be made before sufficient scientific information is available. The distrust that these dichotomies and lack of communication breed has two important and related consequences: (1) the management community tends to question the relevance of environmental research conducted by an independent science community, and (2) the science community tends to question the integrity of the management process.

Free from the requirement to make management decisions, scientists are much more likely to acknowledge uncertainties and the complexities of nature. For example, consider an event that occurred in 1983, the year of the first Chesapeake Bay Agreement. A headline in the *Baltimore Sun* (July 17, 1983) reads "Scientists Wary About Quick Fix for Bay." The article quotes a prominent university scientist as stating in testimony before the state Assembly that "we still don't know very much about nitrogen and the Bay. . . . The nitrogen entering the bay from farm runoff may not be as injurious, pound for pound, as that coming from . . . sewage treatment plants. . . . Buffer strips may not stop much nitrogen from running off farms . . . the bay is not purely a sink [for N, which can escape the Bay in gaseous form]." This left "decision-makers upset and confused . . . some almost cursing, 'saying what is this guy trying to do to us?'" A manager with the Maryland DNR summed up the dilemma by commenting that, "Scientists, being quite honest, present so many options that no action gets taken . . . which is our problem as managers who must take action." In a subsequent interview, Tom Horton of the *Baltimore Sun* (personal notes) quotes Secretary Eichbaum as saying "Ian's [Ian Morris] concerned about a lack of communication between scientists and us? I know he feels that way and I think he's even right, but in most of our experiences in the bay system the scientists have not provided answers as to what to do. They have sat around and complicated the issue, and that's the nature of their job. So at this stage [in the management process] it's not so unusual for scientists to recede into the background. Hopefully, the information they've given us is good enough."

The uncertainties and complexities (large data sets) inherent to environmental science have also led to, arguably, an irrational reliance on mathematical models as predictors of ecological variability and responses to anthropogenic perturbations. This tendency of the management community to view water quality models with considerable favor is understandable. Scientists who develop the models have a vested interest in seeing them used (an example of why it is important to maintain a separation of powers in terms of the generation of scientific information and its use by management). At the same time, they provide an objective means of synthesizing a great deal of information and of predicting both the causes and the consequences of eutrophication (in this case), and they take the "heat" off the decision maker (the model makes the decision). This allows the government to assess blame and institute corrective actions. Herein lies the rub. All of these are attractive (and seductive) features, but all assume that the water quality model provides an accurate representation of the real world.

The current heavy reliance on the 3-D, time-dependent, coupled hydrodynamic water quality model to set nutrient reduction goals and evaluate the success of nutrient control programs is reminiscent of the Patuxent experience. Clearly, this model is significantly improved, but it is still an imperfect cartoon of the real world. It is so tempting to ask the model a question and then believe the answer ("mirror, mirror on the wall") when the most prudent approach is to use the model results in conjunction with other sources of information (monitoring and experimental results that reveal causation). One must also keep in mind that no single model can answer all questions. For example, the current model does not address the dynamics of littoral areas, sea grasses, or food webs. Finally, models may take many years to develop, during which time the playing field and the players may change, including expectations of what the model can and cannot do. The original intent of the model may be modest (e.g., to be used as a trial-and-error tool), but as the results are simplified again and again for nontechnical audiences, expectations can and do become unrealistic. As the cost of the model increases (in terms of time and money) and the corporate memory is lost, the model begins to take on a life of its own and the predictions become reality. Thus, there is a tendency for the management community to reach the conclusion that additional scientific information is no longer needed, a tendency that can be countered by establishing a process of periodic scientific reevaluation of the effectiveness of management actions.

Overcoming Inertia

Clearly, financial incentives in the form of federal and state funding for such actions as the construction of STPs and the implementation of BMPs have played an important role in controlling nutrient loading to surface waters. However, the authorizing legislation and subsequent appropriations are often responses to an environmental catastrophe. In a recent study of the process of environmental governance, Morris and Bell (1988) argue the case that a "major event" is required to stimulate policymakers and managers to take action on environmental issues. They suggested that, in the Chesapeake Bay region, this event was the Chesapeake Bay Study itself. Our analysis certainly supports this contention. By pulling together large numbers of scientists and decision makers from throughout the Bay and its watershed, the EPA Bay Study marked a significant departure from the course of the 1960s and 1970s. Under the auspices of the EPA, it gave rise to a governance structure that would involve citizens, government officials, and scientists in the oversight of environmental research, formulation of policy, and implementation of that policy throughout the entire Bay and its watershed (the Chesapeake Executive Council, Citizens Advisory Committee, Science and Technology Committee, and Implementation Committee). This spawned a decade of research and management activity that was unprecedented in the United States, and ushered in an era that would lead to a more systemwide perspective as the significance of nonpoint sources and water movements through drainage basins and the estuaries of the Bay became increasingly apparent.

Our analysis also suggests that Tropical Storm Agnes was an event of similar impact, which, in effect, set the stage for the EPA Bay Study. Agnes alerted a broad cross-section of the population, including scientists and managers, to the systemwide susceptibility of the Bay to inputs from land. Until Tropical Storm Agnes arrived in 1972, research tended to focus on local problems, a tendency exacerbated by the funding priorities of management agencies that emphasized the effects of power plants, oil spills, and dredging. Pritchard (July 1, 1970, *Baltimore Sun*) states that, "The emphasis on thermal pollution is obscuring the real threat to the Bay, nutrient pollution." This 200-year storm captured the attention of the entire population of the Chesapeake region, including state and federal agencies, elected officials, concerned citizens, and the scientific community. In a terrible way, Agnes reconnected millions of urban and suburban dwellers to nature. People were made keenly aware that they did not just live on a street or in a town, but also in the drainage basin of a creek, in the valley of a river. The storm dramatized how we had changed the very nature of the watershed in just a few decades, stripping the vegetation that once covered it and absorbed and slowed the runoff of rainfall, paving it for roads and parking, and roofing it over with homes. One effect of these land-use patterns was to channel the water that fell with a destructive force never seen before. In retrospect, it is clear that, although the storm delivered a "bullet to the Bay's heart," land use in the watershed had been "loading the gun and softening up the victim for many decades."

The precedent-setting 1981 Patuxent Charrette and the Chesapeake Bay Agreements that followed illustrate the importance of achieving a consensus involving a broad cross-section of a region's social fabric. Events leading up to the Patuxent Charrette and the Charrette itself underscore some of the ingredients needed to achieve a consensus on the nature of the problem and the actions that need to be implemented to solve the problem. Among the more important of these are leadership, trust, and financial incentives. A few powerful individuals had to have more than a passing interest in the problem; they needed to understand the problem well enough to justify action in the context of competing political, economic, and social forces. Such leadership was clearly demonstrated by the actions of Senator Mathias, who formulated the legislation that led to the EPA Bay Program; by Senator Fowler, whose environmental concerns led to a nutrient management plan for the Patuxent River basin; and by the state governors who had the foresight to look beyond their borders in agreeing to clean up the Bay. The Patuxent case in particular illustrates the need for trust. It is unlikely that a truly comprehensive nutrient management plan for the Patuxent River basin would have been agreed upon if it were not for a clear definition of the problem, the establishment of common goals, the existence of independent scientific advice, and mutual respect among the participating parties. In this regard, the university was viewed by Senator Fowler and his associates as a source of information from a disinterested party, an "honest broker." This was critical, as was the presence of managers within the Maryland state government who were willing to listen and even fund research that could (and did) produce evidence that the state and the EPA were wrong in insisting that N loading was not a problem (D'Elia, 1987; D'Elia et al., 1986).

The main impact of these actions and the "major" events that gave rise to them was to raise the plight of the Bay to a new level of public and political consciousness. In this context, it is important to note that, although there were (and are) few who would take exception to the course set by the 1983 Bay Agreement, important decisions were made on the basis of relatively little scientific information—decisions that would have profound social and economic consequences. Agreements were consummated by high-ranking government officials based on perceptions and the "common sense" of the day. The impact of the EPA Bay Study was not related as much to new scientific information as it was to the large number and diversity of individuals and institutions involved in the process. The real genius of the study was in synthesizing and disseminating existing environmental information and scientific understanding, and in providing the political climate needed to galvanize decision makers throughout the Bay's multistate watershed. The process itself, rather than the information it produced, led to the Bay Agreement and launched an unprecedented period of legislative, management, public, and research activity.

NOTES

1. The degradation of water quality occurs when assimilation capacity is exceeded. The degradation is expressed by such phenomena as accumulations of algal biomass, noxious algal blooms, decreases in water clarity, depletion of oxygen, and related losses of plant, animal, and insect life.

2. Environmental research is defined as activities that generate technical information about nutrient enrichment upon which the management of nutrient inputs can be based. Management is considered to be primarily a government activity that includes the formulation of environmental policy, regulations, and agreements.

3. The term *anthropogenic* is generally used to identify sources of pollutants that stem from human activities—manufacturing, farming, waste disposal, etc. For purposes of this analysis, anthropogenic nutrient inputs include inputs from point sources (such as wastewater discharges) and diffuse sources (for example, runoff from agricultural development, atmospheric deposition).

4. Hurricane Agnes caused devastating coastal flooding from Florida to New York. By the time the storm reached Chesapeake Bay, it had been downgraded to the level of a tropical storm.

5. A massive nuisance bloom of blue-green algae in the upper Potomac in 1983 was attributed to a combination of events that resulted in the release of excess phosphorus from the sediments (Jaworski, 1990).

REFERENCES

American Society of Limnology and Oceanography. 1972. Nutrients and eutrophication: the limiting-nutrient controversy. Proceedings of the 1971 Symposium on Nutrients and Eutrophication. Lawrence, Kansas: Allen Press.

Bayley, S., H. Rabin, and C. H. Southwick. 1968. Recent decline in the distribution and abundance of eurasian milfoil in Chesapeake Bay. Chesapeake Science 9:173–181.

Bayley, S., V. D. Stotts, P. F. Springer, and J. Steenis. 1978. Change in submerged aquatic macrophyte populations at the head of Chesapeake Bay, 1958–1975. Estuaries 1:171–182.

Boynton, W. R., W. M. Kemp, and C. G. Osborne. 1980. Nutrient fluxes across the sediment-water interface in the turbid zone of a coastal plain estuary. Pp. 93–109 in Estuarine Perspectives, V. S. Kennedy, ed. New York: Academic Press.

Boynton, W. R., W. M. Kemp, and C. W. Keefe. 1982. A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production. Pp. 69–90 in Estuarine Comparisons, V. S. Kennedy ed. New York: Academic Press.

Bunker, S. M., and G. V. Hodge. 1982. The legal, political and scientific aspects of the Patuxent River nutrient control controversy. 8th Annual Coastal Society Conference, Baltimore, Md.

Carpenter, J. H., D. W. Pritchard, and R. C. Whaley. 1969. Observations of eutrophication and nutrient cycles in some coastal plain estuaries. Pp. 210–221 in Eutrophication: Causes, Consequences, Correctives. Proceedings of the 1967 International Symposium on Eutrophication. University of Wisconsin. Washington, D.C.: National Academy of Sciences.

Chesapeake Bay Commission. 1985. Choices for the Chesapeake: The first biennial review of the action agenda. Report to the General Assemblies of Maryland and Virginia.

Chesapeake Research Consortium. 1976. The Effects of Tropical Storm Agnes on the Chesapeake Bay Estuarine System. Publ. No. 54. Baltimore, Md.: Johns Hopkins University Press.

Chesapeake Research Consortium. 1977. Proceedings of the Bi-State Conference on the Chesapeake Bay, April 27–29, 1977. Publ. No. 61

Clark, L. J., D. K. Donnelly, and O. Villa. 1973. Nutrient enrichment and control requirements in the upper Chesapeake Bay. EPA Report No. 903/9-73-002-a.

Clark, L. J., V. Guide, and T. H. Pheiffer. 1974. Summary and conclusions: Nutrient transport and accountability in the lower Susquehanna River basin. Tech. Report 60: Annapolis Field Office, Region III, Environmental Protection Agency.

D'Elia, C. F., J. G. Sanders and W. R. Boynton. 1986. Nutrient enrichment studies in a coastal plain estuary: phytoplankton growth in large-scale continuous cultures. Canadian Journal of Fisheries and Aquatic Sciences 43:397–406.

D'Elia, C. F. 1987. Nutrient enrichment of Chesapeake Bay. Environment 29:6–33.

Eichbaum, W. 1984. The Chesapeake Bay: Major research program leads to innovative implementation. Environmental Law Reporter 14:10237–10245.

Fisher, D. C., and M. Oppenheimer. 1991. Atmospheric nitrogen deposition and the Chesapeake Bay estuary. AMBIO 20:102–108.

Flemer, D. A., D. H. Hamilton, J. A. Mihursky and C. W. Keefe. 1969. The effects of thermal loading and water quality on estuarine primary production. An interpretive report for the period August 1968 to August 1969 to the U.S. Department of the Interior, Office of Water Resources Research, Washington, D.C.

Heinle, D. R., D. H. Hamilton, and D. A. Flemer. 1970. A unified approach to research on Chesapeake Bay. Chesapeake Biological Laboratory, Ref. No. 70–32.

Heinle, D. R., C. F. D'Elia, J. L. Taft, J. S. Wilson, M. Cole-Jones, A. B. Caplins, and L. E. Cronin. 1980. Historical review of water quality and climatic data from Chesapeake Bay with emphasis on effects of enrichment. Report to EPA, CRC Publ. No. 84, UMCEES Ref. No. 80-15CBL.

Hydroscience, Inc. 1975. Wasteload Allocation Study. Maryland Department of Natural Resources, Water Resources Administration, Annapolis, Md.

Jaworski, N. A. 1981. Sources of nutrients and the scale of eutrophication problems in estuaries. Pp. 83–110 in Estuaries and Nutrients, B. J. Neilson and L. E. Cronin, eds. Totowa, N.J.: Humana Press.

Jaworski, N. A. 1990. Retrospective of the water quality issues of the upper Potomac estuary. Aquatic Science 3:11–40.

Jaworski, N. A., D. W. Lear, and J. A. Aalto. 1969. A technical assessment of current water quality conditions and factors affecting water quality in the upper Potomac estuary. U.S. Department of the Interior Tech. Rep. No. 5.

Jaworski, N. A., D. W. Lear, and J. A. Aalto. 1972. Nutrient management in the Potomac estuary. Pp. 246–273 in Nutrients and Eutrophication, G.E. Likens, ed. American Society of Limnology and Oceanography. Lawrence, Kansas: Allen Press.

Jaworski, N. A., P. M. Groffman, A. A. Keller and J. C. Prager. 1992. A wastewater nitrogen and phosphorus balance: The upper Potomac River basin. Estuaries 15:83–95.

Kemp, W. M., and W. R. Boynton. 1984. Spatial and temporal coupling of nutrient inputs to estuarine primary production: The role of particulate transport and decomposition. Bulletin of Marine Science 35:522–535.

Kemp, W. M., R. R. Twilley, J. C. Stevenson, W. R. Boynton, and J. C. Means. 1983. The decline of submerged vascular plants in upper Chesapeake Bay: Summary of results concerning possible causes. Journal of the Marine Technology Society 17:78–89.

Ketchum, E. H. 1969. Eutrophication of estuaries. Pp. 197–209 in Eutrophication: Causes, Consequences, Correctives. Proceedings of the 1967 International Symposium on Eutrophication, University of Wisconsin. Washington, D.C.: National Academy of Sciences.

Lomax, K., and J. C. Stevenson. 1981. Diffuse Source Loadings from Flat Coastal Plain Watersheds: Water Movement and Nutrient Budgets. Annapolis, Md.: Tidewater Administration, Maryland Department of Natural Resources.

Maryland Sea Grant College Program and Virginia Sea Grant College Program. 1992. Dissolved Oxygen in the Chesapeake Bay: A Scientific Consensus. College Park, Md.: Maryland Sea Grant College.

Morris, L. and W. H. Bell. 1988. Coastal seas governance: an international project for management policy on threatened coastal seas. Maryland Law Review 47:481–496.

National Research Council. 1969. Eutrophication: Causes, Consequences, Correctives. Proceedings of the 1967 International Symposium on Eutrophication, University of Wisconsin. Washington, D.C.: National Academy of Sciences.

Neilson, B. J., and L. E. Cronin, eds. 1981. Estuaries and Nutrients. Totowa, N.J.: Humana Press.

Nixon, S. W., and M. E. Q. Pilson. 1983. Nitrogen in estuaries and coastal marine ecosystems. Pp. 565–648 in Nitrogen in the Marine Environment, E. J. Carpenter and D. G. Capone, eds. New York: Academic Press.

Officer, C. B., and J. H. Ryther. 1977. Secondary sewage treatment versus ocean outfalls: An assessment. Science 197:1056–1060.

Officer, C. B., R. B. Biggs, J. L. Taft, L. E. Cronin, M. A. Tyler, and W. R. Boynton. 1984. Chesapeake Bay anoxia: Origin, development, and significance. Science 223:22–27.

Orth, R. J., and K. A. Moore. 1983. Chesapeake Bay: An unprecedented decline in submerged aquatic vegetation. Science 222:51–53.

Pritchard, D. W. 1969. Dispersion and flushing of pollutants in estuaries. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers 95:115–124.

Ryther, J. H., and W. M. Dunstan. 1971. Nitrogen, phosphorus, and eutrophication in the coastal marine environment. Science 171:1008–1013.

Schindler, D. W. 1974. Eutrophication and recovery in experimental lakes: Implications for lake management. Science 184:897–899.

Schindler, D. W. 1977. Evolution of phosphorus limitation in lakes. Science 195:260–262.

Seliger, H. H., J. A. Boggs, and W. H. Biggley. 1985. Catastrophic anoxia in the Chesapeake Bay in 1984. Science 228:70–73.

Smith, D. E., M. Leffler, and G. Mackiernan, eds. 1992. Oxygen Dynamics in the Chesapeake Bay. Maryland Sea Grant, College Park, Md.

Southwick, C. H., and F. W. Pine. 1975. Abundance of submerged vascular vegetation in the Rhode River from 1966–1973. Chesapeake Science 16:147–151.

Staver, K., R. Brinsfield, and J. C. Stevenson. 1987. Strategies for reducing nutrient and pesticide movement from agricultural land in the Chesapeake region. In Toxic Substances in Agricultural Water Supply and Drainage. Proceedings of National Meeting, U.S. Committee on Irrigation and Drainage, Denver, Colo.

Staver, K., R. Brinsfield, and J. C. Stevenson. 1989. The effect of best management practices on nitrogen transport into Chesapeake Bay. In Toxic Substances in Agricultural Water

Supply and Drainage: An Environmental Perspective. J.B. Summers and S.S. Anderson, eds. Denver, Colo.: U.S Committee on Irrigation and Drainage.

Stevenson, J. C., and N. M. Confer. 1978. Summary of available information on Chesapeake Bay submerged aquatic vegetation. Final Report U.S. Fish and Wildlife Service, No. 14-16-008-1255. Washington, D.C.

Stevenson, J. C., L. W. Staver, and K. Staver. 1993. Water quality associated with survival of submersed aquatic vegetation along an estuarine gradient. Estuaries 16(2): (in press).

Twilley, R. R., W. M. Kemp, K. W. Staver, and J. C. Stevenson. 1985. Nutrient enrichment of estuarine submersed vascular plant communities. I. Algal growth and effects on production of plants and associated communities. Marine Ecology—Progress Series 23:179–191.

U.S. Army Corps of Engineers. 1973. Chesapeake Bay Existing Conditions Report. Baltimore, Md.: Department of the Army.

U.S. Army Corps of Engineers. 1977. Chesapeake Bay Future Conditions Report. Baltimore, Md.: Department of the Army.

U.S. Fish and Wildlife Service. 1969. The National Estuarine Pollution Study. Washington, D.C.: Department of the Interior.

U.S. Fish and Wildlife Service. 1970. National Estuary Study. Washington, D.C.: Department of the Interior.

U.S. Environmental Protection Agency. 1982. Chesapeake Bay Program Technical Studies: A synthesis. Washington, D.C.

U.S. Environmental Protection Agency. 1983a. Chesapeake Bay Program, Choices for the Chesapeake: An Action Agenda, 1983 Chesapeake Bay Conference Report, F. H. Flanigan, ed. Annapolis, Md.

U.S. Environmental Protection Agency. 1983b. Chesapeake Bay Program: Findings and Recommendations. Washington, D.C.

U.S. Environmental Protection Agency. 1983c. Chesapeake Bay Program: A Framework for Action. Washington, D.C.

U.S. Environmental Protection Agency. 1983d. Chesapeake Bay Program: A Profile of Environmental Change. Washington, D.C.

U.S. Environmental Protection Agency. 1985. Chesapeake Executive Council, Chesapeake Bay Restoration and Protection Plan. Annapolis, Md.

U.S. Environmental Protection Agency. 1986. Chesapeake Bay Program, Scientific and Technical Advisory Committee. Nutrient Control in the Chesapeake Bay. Annapolis, Md.

U.S. Environmental Protection Agency. 1988. A Commitment Renewed: Restoration Progress and the Course Ahead Under the 1987 Bay Agreement. Chesapeake Bay Program, Implementation Committee. Annapolis, Md.

U.S. Environmental Protection Agency. 1992. Chesapeake Bay Program, Progress Report of the Baywide Nutrient Reduction Reevaluation. Annapolis, Md.

Vollenweider, R. A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters with particular reference to nitrogen and phosphorus as factors in eutrophication. OECD Technical Report DAS/CSI 68(27), Paris, France.

Vollenweider, R. A. 1976. Advances in defining critical loading levels of phosphorus in lake eutrophication. Memorie—Istituto Italiano de Idrobilogia 33:53–83.

Walter, M. F., T. S. Steenhuis, and D. Haitch. 1979. Nonpoint source pollution control by soil and water conservation practices. Transactions—American Society of Agricultural Engineers 22:834–840.