Science, Policy and Coastal Eutrophication: the Chesapeake Experience

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Abstract

Science and Policy Development Related to Eutrophication of Coastal Ecosystems

In assessing the policy options appropriate to addressing hypoxia in the northwestern Gulf of Mexico, it is helpful to learn from experiences in the use of science elsewhere. The Chesapeake Bay and other U.S. coastal systems, and northwestern Europe provide instructive case studies. Coastal eutrophication commonly results from nutrient inputs from diffuse sources, thus effects are not easily seen as connected to causes. Both science and policy must address the scale mismatches over space (responsible actions far removed from effects) and time (present, pre-existing and future conditions) scales and human activity sectors (e.g., agriculture and fisheries).

At the first level, science must address the question of whether such effects as hypoxia or algal blooms have worsened over time and whether they have harmful or undesirable consequences. Next, ties need to be made between nutrient inputs and responses (e.g., in the Chesapeake major disputes were waged as to whether N or P limited algal production). Models have been very helpful in summarizing complex science in a way that policy makers could pose "what if" questions and have, in some cases, become the central technical tool of management. In the Chesapeake early models were used to justify the goal of 40 percent reduction in controllable nutrients and more sophisticated models are now used to reassess goals and address subsequent policy issues, such as the effect of Clean Water Act ozone reduction on water quality. Finally, policy makers, and society in general, are unlikely to undertake ambitious environmental restoration goals without technological advances that make them feasible (for example, the application of biological nutrient removal for sewage treatment and cost-effective best management practices in agriculture).

Introduction

Eutrophication, the excessive enrichment of aquatic ecosystems which leads to increased primary productivity, noxious algal blooms, food-chain alterations, and depletion of dissolved oxygen, is a widespread phenomenon in coastal waters of developed nations. Furthermore, contrary to many marine pollution problems which have been ameliorated by waste treatment and other controls, coastal eutrophication has been in ascendancy during the latter half of the twentieth century (National Research Council, 1994). This is due in large measure to the important contributions of diffuse sources of nutrient inputs—from agricultural fertilizers, runoff from developed land, atmospheric deposition, and soil erosion— in

addition to more controllable point sources, such as sewage or industrial discharges. The multitude of sources and the remote nature of many of the sources make them difficult to identify, much less control.

In a number of places in the United States, Europe and Japan, once the degradation of the environment due to coastal eutrophication was identified, extensive efforts are being undertaken to reduce the point and diffuse sources of nutrient inputs from human activities. Science has played and is playing a major role in identifying the causes and consequences of coastal eutrophication and in finding solutions. Although complete success has been met nowhere, progress is being made in establishing nutrient reduction goals, targeting sources and achieving reductions. Perhaps the most famous, and certainly the most ambitious, of these efforts is in the Chesapeake Bay and its watershed.

To help set the stage for discussion of management of widespread oxygen depletion, or hypoxia, attributed to eutrophication in the northern Gulf of Mexico, I will briefly review the role science has played in the development of policy and management solutions for controlling nutrient over-enrichment in the Chesapeake Bay. My goal is to examine the role of science in addressing critical policy questions so that lessons may be applied to the case of hypoxia in the northern Gulf of Mexico.

The Challenge of Scale Mismatches

At the heart of the problem of understanding and managing coastal eutrophication is the challenge of scale mismatches inherent in the problem. As Lee (1993) puts it: "when human responsibility does not match the spatial, temporal or functional scale of natural phenomena, unsustainable use of resources is likely, and it will persist until the mismatch of scales is cured."

In the case of coastal eutrophication, perhaps the most obvious scale mismatch is on the **spatial scale**. In contrast to most coastal environmental and resource issues, for example waste disposal, coastal development, habitat destruction, and resource exploitation, the sources of eutrophication may not be considered coastal at all. They may originate far up the watershed, hundreds of miles away, or even from outside of the watershed in the case of atmospheric deposition. This poses significant challenges for science in addressing these large scales. Even more importantly, it is hard for people to be aware of or accept that their activities in Pennsylvania or Iowa may be causing a problem so far away at the coast. Furthermore, they may see efforts to reduce nutrient inputs without benefit to them. The beneficiaries are those on the coast in Maryland and Virginia or Louisiana and Texas.

In addition, there are mismatches on a **functional scale**, for example the cause of coastal eutrophication may be related to agriculture, waste disposal, or power generation, but the deleterious consequences may be felt in marine fisheries. Even within the coastal and marine environment it is difficult to connect human responsibility for fisheries with that for water quality or, in the case of the Mississippi delta, wetland restoration with offshore hypoxia.

Finally, there are important **temporal scale** mismatches. In the case of coastal eutrophication these frequently occur because of a lack of understanding of what conditions were like before the increase in anthropogenic inputs of nutrients and to what degree and how rapidly the system will recover.

Key Questions

There are several key questions which must be at least partially addressed before public support and

political will can be marshaled sufficiently to undertake and affect the control of nutrient inputs into coastal environments in order to reduce hypoxia. In logical order they are:

1. Is the hypoxia a natural phenomenon? Has it worsened?
2. What are the consequences of hypoxia for resources and environmental quality? Does it matter?
3. Is hypoxia caused by increased nutrient inputs from human activities?
4. What are the sources of these excess nutrients?
5. What will be the effect of reducing these nutrient inputs?
6. How can the sources of nutrients be feasibly reduced?
7. What are the incentives for reducing these sources of nutrients?

All of these pose significant challenges to science and technology. In order to effect solutions, it is not sufficient just to describe hypoxia, put it into historical context, identify causes, pinpoint sources and predict the consequences of nutrient inputs, as difficult as these task are. Science and technology must also help find feasible means for reducing inputs and contribute to the development of incentives to accomplish this goal. I will briefly review how these questions were or are being addressed in the case of the Chesapeake Bay.

Experience of the Chesapeake Bay

The development of scientific understanding of the effects of nutrient loading to the Chesapeake Bay and the impact that science had on policy development has been thoroughly reviewed by Malone et al. (1993). Based on their observations and my own I review how the seven questions have been addressed for the Chesapeake.

Question 1: Is the hypoxia a natural phenomenon?

Although anoxic conditions in the deeper waters of the Chesapeake Bay had been observed since measurements were first made, it was not until 1984 that Officer et al. argued in a paper in *Science* that there was an increase in oxygen depletion between 1950 and 1980. This interpretation engendered controversy and Seliger et al. (1985) countered that when corrected for river inflow, which increases density stratification and nutrient mass loading, there was not a statistically significant trend (Seliger et al., 1985). About the same time, results from studies initiated to investigate the dramatic reduction of submersed aquatic vegetation in the Bay during the 1970's also implicated increased nutrient loading (Kemp et al., 1983). Interestingly, growing public concern about the health of the Bay, coupled with an assessment process begun in the late 1970's, set the stage for policy commitments in 1987 to reduce controllable nutrients by 40 percent by the year 2000 even though Question 1 had not been fully answered.

Subsequently, Cooper and Brush (1991) and Cooper (1995) were able to demonstrate from biological and chemical indicators in cores that: (a) hypoxia was part of the Bay's ecology for a long time; (b) eutrophication due to human activities began with extensive land clearing in the late 18th century; and (c) anoxic conditions have become more frequent and persistent during the mid-20th century in association with both rapid population growth and the advent of widespread use of artificial fertilizers. From their and other work, one can sketch a modern environmental history of the Chesapeake Bay (Table 1) in the context of which can be placed the more recently observed deterioration of the environment and the restoration goals.

Table 1.
The modern environmental history of the Chesapeake Bay

Period	Years	Description
Pre-Colonial and Early Colonial	(<1730)	Watershed is mostly forested, nitrogen flux to the Bay *about 15% of present level*
Agrarian	(1740–1860)	Deforestation for expansion of agriculture leads to increased soil erosion and loss of forest nutrient retention capabilities, which in turn leads to decreased water clarity and increased organic production
Agrarian	(1880–1940)	Urban population growth results in collection and discharge of sewage; industrial development results in increased inputs of trace metals; mechanical harvesting greatly reduces oyster populations resulting in a substantial reduction of benthic filter feeding
Petrochemical	(1950–1980)	Increased use of petroleum and manufacture of synthetic organic compounds results in severe contamination of port areas and widespread, low level contamination elsewhere; use of artificial fertilizers and increased combustion of fossil fuels increases diffuse loading of nutrients, leading to intensified anoxia and loss of submersed aquatic vegetation
Sustainability?	(>1980)	Recognition of problems associated with nutrient over-enrichment leads to ban of phosphates in detergents, nutrient removal in sewage treatment, improved agricultural management practices, population growth management, reduction of emissions from vehicles, and restoration of oyster populations for environmental rather than commercial reasons

Question 2: What are the consequences of hypoxia?

Somewhat surprisingly, very little has been done to quantify the impacts of hypoxia on living resources, either before the 1987 policy commitment to reduce nutrient loading or subsequently. Although the effects of seasonal hypoxia on benthic organisms have been well documented (Holland et al., 1987) and the physiological tolerance of motile fishes and invertebrates indicate that they cannot survive long in near-anoxic waters (Sea Grant Programs, 1992), the effects on fisheries and shellfisheries have not been directly assessed. In fact, landings data do not show an increase or decline in the total fisheries productivity during the latter half of the

twentieth century, although there has been a shift in harvested biomass from benthic (e.g., oysters) to pelagic (e.g., menhaden) species. Rather, the reductions in important fishery resources that have occurred are thought to be primarily the result of over fishing, habitat modification and barriers to anadromous fish migration. Hypoxia in the Chesapeake Bay has generally been assumed to be detrimental to living resources, but its role relative to these other pressures is not well understood.

On the other hand, scientific understanding of exchange of nutrients with bottom sediments indicates that anoxia has a positive feedback to eutrophication (Boynton et al., 1995), further reducing water quality. Hypoxia in bottom waters results in episodic fluxing of phosphorous from sediments. Persistent anoxia can also greatly reduce denitrification rates by shutting down nitrification of ammonium. The net effect is rapid recycling of phosphorous and attenuation of the nitrogen sink, resulting in increased phytoplankton production, decreased water clarity, and increased oxygen demand in bottom waters.

More attention has been given to the other effects of eutrophication on living resources, such as the loss of submersed aquatic vegetation, decreases in water clarity, and changes in food chains. Several lines of evidence suggest that nutrient enrichment, at least during this century, has not resulted in increases in harvestable secondary production. The Chesapeake Bay is characterized by high primary productivity relative to nutrient loading and high secondary productivity relative to its primary productivity (Nixon et al., 1986). This suggests that factors other than nutrient availability are controlling secondary production in this system at this point in its eutrophication history.

Question 3: Is hypoxia caused by increased nutrient inputs?

The Chesapeake Bay restoration effort is well known for its commitment to reduce controllable loadings of nutrients by 40 percent, a commitment which is now involving hundreds of waste discharges, thousands of farmers and citizens, and massive investments of public and private funds. It is important to keep in mind that it has been just since the early 1980's that the notion that the Bay was suffering ill effects from excess nutrients began to gain wide acceptance (Malone et al., 1993). During the late 1960's, massive algal blooms, oxygen depletion and fish kills in the upper tidal (freshwater) Potomac River led to large investments in the early 1970's for sewage treatment facilities for the metropolitan Washington area. These treatments included removal of phosphorus, which was known to be the culprit in causing eutrophication in freshwater lakes, as well as BOD. Substantial improvements in water quality in the tidal freshwater Potomac resulted (Jaworski, 1990).

It took about a decade more to conclude that the Bay had undergone widespread eutrophication, to understand that excess nitrogen as well as phosphorus was posing a problem, and to effect policy for broader control of point sources of nitrogen and phosphorous. The scientific community first presented inferential evidence such as data on trends in nutrient loadings and nutrient ratios which suggested that nitrogen may be limiting primary production in more saline parts of the Bay (Boynton et al., 1982). This evidence suggested that nitrogen removal was needed in new sewage treatment facilities then being planned for the upper Patuxent River estuary in order to avoid further declines in water quality, a view that conflicted with the position of federal and state agencies that only phosphorus removal was required. The science and uncertainties were debated in court and in a conflict-resolution conference which concluded with the agreement to remove nitrogen as well as phosphorus in these new facilities. Only later was more direct evidence of nitrogen limitation of phytoplankton growth provided from mesocosm studies (D'Elia et al., 1986). Meanwhile, investigations of the cause of the widespread

decline of submersed aquatic vegetation contributed more to the understanding of the consequences of nutrient enrichment than did studies addressing the relationship of nutrients to hypoxia (Malone et al., 1993). These findings also brought attention to the importance of nonpoint sources to the overall eutrophication of the Bay.

Development of policies which culminated in the regional federal-state commitment to reduce controllable inputs of nitrogen and phosphorous by 40 percent were initiated with very modest understanding of the relationship of these inputs to hypoxia. As Malone et al. (1993) observed: "In a qualitative way, these links made sense, but the scientific evidence needed to make the case remained weak." Nonetheless, in 1983 the EPA published a framework for action for the Chesapeake Bay which focused 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." This set the stage for the first multi-jurisdictional Bay Agreement, a flurry of legislative actions, the establishment of a monitoring program, and a decade of intense scientific studies of nutrient dynamics. Findings of these studies have greatly enriched our understanding of the sources of nutrients, their effects on plankton production and submersed aquatic vegetation, nutrient cycling and loss (Boynton et al., 1995), and their effects on hypoxia (Sea Grant Programs, 1992). These have confirmed the wisdom of the policies developed earlier based on much more limited scientific evidence.

Question 4: What are the sources of these excess nutrients?

Although it was long understood that nonpoint sources of nutrients must be significant for an estuary with such a large watershed as the Chesapeake Bay, early management efforts focused on controlling point sources, particularly sewage treatment plants. Concerns about the health of the Bay led to a five year study begun in 1977 which yielded the first good estimates of total nutrient load to the Bay. These showed the quantitative importance of nonpoint sources. Current best estimates are that agricultural lands, developed areas, and atmospheric deposition contribute 2.5 and 1.8 times the amount of nitrogen and phosphorus, respectively, that point sources deliver (Table 2). As a consequence, extensive efforts are underway to reduce nutrient losses from agriculture—by applying "best management practices" and nutrient management procedures throughout the watershed—and from developed areas—through sediment erosion controls, storm water management, and limitations to shoreline development.

Table 2.
Estimated portions of total nutrient loads that enter the Chesapeake Bay from land-based sources and activities, i.e., excluding inputs from the ocean (Magnien et al., 1995).

	N	P
Forests	18%	3%
Agriculture	39%	49%
Development	9%	8%
Atmosphere*	11%	6%
Point Sources	23%	34%

* Includes deposition directly on the water; atmospheric N deposition on land accounts for an additional 16% of total N load, but is included as part of forest, agriculture and developed land sources.

The agreement to reduce controllable inputs of nitrogen and phosphorus into the Chesapeake Bay includes only a portion of the total nutrient loadings apportioned in Table 2. Excluded from the total controllable pool are inputs into the small parts of the watershed located in Delaware, New York, and West Virginia, states not signatories to the Chesapeake Bay Agreement. Furthermore, there is assumed to be base inputs from various land uses (i.e. agriculture, developed land, and forests) which are not amenable to reduction. Also, atmospheric inputs were not

included at all in the definition of controllable sources, but these too are receiving increased attention for control strategies, particularly for nitrogen. This is a difficult challenge because a significant fraction of the atmospheric deposition of nitrogen in the watershed emanates from sources outside of the watershed, particularly from the Ohio River basin.

Question 5: *What will be the effect of reducing these nutrient inputs?*

The expectations regarding the degree of improvement of conditions in the Bay which could be achieved by reduction of controllable nutrients by 40 percent were general, hopeful and not very quantitative when the policy was adopted. Since then, as mentioned earlier, much has been learned about the dynamics of nutrients in the Bay and the relationship of nutrient inputs to both hypoxia and conditions for growth of submersed aquatic vegetation. This increased understanding has been rather rapidly incorporated into various models which allow a scientific assessment of the effects of the nutrient reductions targeted and others which may be achievable.

Particularly prominent has been the three-dimensional, time-variable numerical model of the Chesapeake Bay which has evolved over the last decade or more (Figure 1). This model incorporates hydrodynamic, geochemical and biological processes and allows one to predict dissolved oxygen conditions and nutrient concentrations (useful in assessing the effects on submerged vegetation) as a function of point and nonpoint source inputs. The linked watershed model includes inputs from atmospheric deposition and meteorological models and is adjustable for changes in land use. The watershed model determines the effects of nutrient loading changes throughout the watershed on delivery of nutrients by rivers to the Bay but is, in general, not founded on the same level of scientific understanding as is the Bay model.

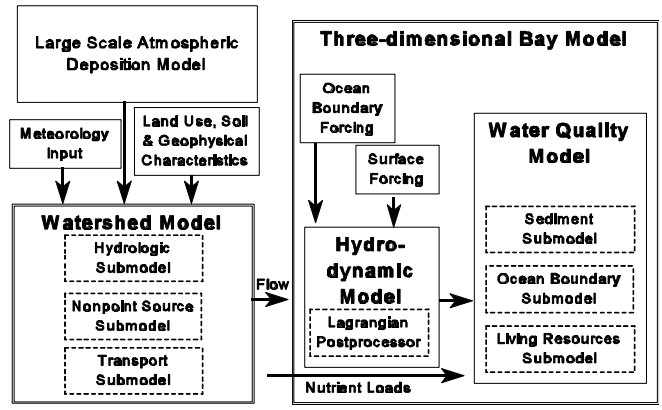

Figure 1.
Schematic depiction of the linked watershed and three dimensional Chesapeake Bay numerical models used to guide assessments of the relationship of nutrient inputs to hypoxia and other ecosystem effects in the Chesapeake Bay Program.

These models have been used to predict changes in the extent of hypoxia in the Bay under future conditions. This has allowed a re-evaluation of the original goal of 40 percent reductions of nitrogen (about 20 percent of total input) and phosphorus (about 30 percent of the total input). The models predict a decrease in anoxic volume-days of just 21 percent with a 40 percent reduction in controllable nutrients and even at the limits of nutrient control technology anoxia (<1 mg/l dissolved oxygen) would only be reduced by 32 percent. Also depicted in Figure 2 are the effects on anoxia of reducing atmospheric nitrogen inputs through implementation of Clean Air Act Amendment's goals for ozone attainment via reductions in NO_x emissions. These model predictions inject some reality for environmental quality objectives: the Chesapeake Bay will exhibit significant summer hypoxia even with more rigorous pollution controls as long as much of the watershed is in agricultural production employing artificial fertilizers, handles the wastes of 15 million people, and receives the residuum from extensive fossil fuel combustion.

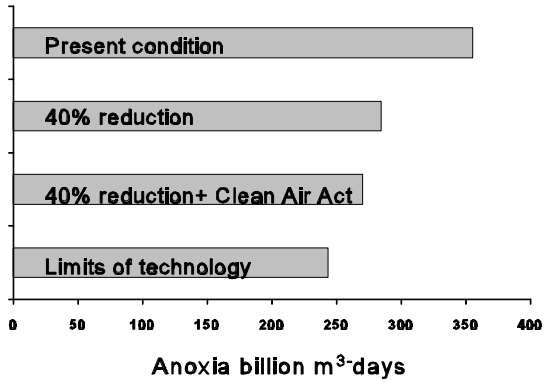

Figure 2.
Predicted effects on the extent of anoxia in the Chesapeake Bay as a result of achieving various management goals (Thomann, et al., 1994).

More optimistically, there may be significant environmental quality improvements beyond the reduction of anoxia in the Bay as a result of meeting the 40 percent reduction. These include significant improvements in dissolved oxygen in waters presently hypoxic, but not anoxic, and reduced ambient concentrations of nutrients to levels which permit growth and survival of submersed aquatic vegetation (Dennison, et al., 1993).

The watershed and Bay models also allow scientists and managers to identify the processes and responses which are poorly known but significantly influence the models' predictions so that research and monitoring may be strategically focused. Among the critical questions now receiving attention are how agricultural practices affect rates of loss of nitrogen into ground water, residence time in ground water for the wide variety of geological conditions which exist in the Bay, nutrient retention as a function of forest age, and denitrification processes in wetlands and Bay sediments. Resolution of such issues is important at this juncture because, although phosphorus concentrations have been significantly reduced in the Bay as a result of point and nonpoint source reductions, riverine fluxes of nitrogen and concentrations of nitrogen in the Bay have not yet decreased (Boynton, et al., 1995).

Question 6: How can the sources of nutrients be feasibly reduced?

Experience indicates that until feasible solutions to problems are identified, the will to correct the problems will not be mobilized no matter how undesirable the consequences. With regard to nutrient reductions in the Chesapeake, the dramatic improvements in water quality which resulted from advanced waste treatment at the top of the Potomac estuary had built some confidence that feasible, albeit expensive, solutions could be found. In addition, following this experience and the experience of the Great Lakes, phosphate detergents were banned in many jurisdictions in the Chesapeake watershed. However, the difficulties and formidable costs associated with reducing sources of nitrogen were, in no small measure, responsible for the denial by both federal and state agencies that the Bay was being over-enriched with nitrogen. The demonstration of the feasibility of biological nutrient removal (BNR) as a cost-effective sewage treatment technology helped overcome this resistance. BNR is now being implemented or planned for most sewage treatment works discharging to the tidal waters of the Bay.

Controlling the agricultural sources of nutrients has also proven challenging. Upton Sinclair once observed: "It is difficult to get a man to understand something when his salary depends upon his not understanding it." Similarly, there was at first strong denial that agricultural uses of fertilizers and animal wastes could be contributing to eutrophication in the Chesapeake Bay, so far away. To a certain degree, such skepticism still exists in the agricultural community as it confronts additional costs in implementing BMPs and the threat of government regulation. Nonetheless, extensive efforts are underway to implement management practices such as minimum-till, buffer strips, and reforestation of riparian areas. However, there is growing evidence that such conventional methods are not as effective as projected in controlling nitrogen losses. Many of these methods were developed to reduce soil losses. Although they are relatively effective in controlling phosphorus losses, they

are less effective for the retention of nitrogen, which is more soluble and escapes into ground water. Other approaches, such as winter cover crops, precision agriculture which minimizes the amount of fertilizer applied to just that required by the crop, and new animal food formulations which reduce nutrient losses via manure, are beginning to be applied, but are more costly.

The commitment of the states to reduce nutrient inputs to the Chesapeake Bay has also become a pervasive organizing principle for many other aspects of environmental management. The importance of forests in the watershed in retaining nutrients is being considered in forestry and reforestation. Retention of nutrients is also an important issue in the conservation of nontidal wetlands. Management of human population growth is another issue that is being pursued in part because of the impact of land development and sprawl on nutrient inputs to the Bay. These growth management goals coincide with those related to regional transportation, infrastructure, natural heritage, and community development. And, finally, as mentioned above, reduced NO_x emissions are being sought not only because of concerns about their effects on ground level ozone but also because of their contributions via atmospheric deposition of nutrients. In short, commitments to reduce nutrient inputs are providing impetus to move toward ecosystem management of the Chesapeake Bay and its watershed.

Question 7: What are the incentives for reducing these sources of nutrients?

It is not enough to identify the problem, its causes and feasible solutions. The solutions must be mandated or there need to be incentives to implement the solutions voluntarily. In the Chesapeake, these incentives included state and federal financial assistance in construction and upgrading of sewage treatment plants and implementing stormwater management programs. In addition technical assistance and matching funds have been provided to assist farmers in implementing BMPs. However, these sources of public financing have been greatly reduced in recent years as a result of changes in federal legislation and the competing fiscal pressures at the federal and state level. Realizing that one often cannot simply mandate nutrient reductions from non-point sources from Harrisburg, Annapolis or Richmond, the Chesapeake Bay Program is pursuing Tributary Strategies which involve the diverse local interests within each of some 30 sub-watersheds to find effective community-based approaches to meet goals for reducing nutrient inputs. These solutions may include trading off reductions from one source for another, tax incentives, growth management, and local ordinances.

Another motivating factor, particularly for communities located well up in the watershed, far-removed from the Chesapeake Bay, is that there are many local benefits to be had in reducing nutrient inputs. These include improving water quality in lakes, streams and rivers, reducing groundwater contamination, managing population growth, forested and agricultural land preservation, and improving air quality. Also, in the long term there are frequently cost savings in pollution prevention. For example, effective nutrient management in agriculture may actually save costs by reducing the amount of fertilizer which must be purchased.

Driving Forces

There are a number of reasons why the Chesapeake Bay region has led the way in terms of recognition of the effects of large scale eutrophication and making major commitments to reduce nutrient inputs in order to restore this ecosystem. These include at least the following:

- The region has a history of sustained scientific investigation, including strong basic research and monitoring.
- Many people regularly see the Bay and enjoy it. Catastrophic events and decimated resources brought attention to the problem.
- There were very effective political

champions who emerged at the right time.

- Even though the region is large, there is a sense of community or a sense of "place" about the Chesapeake. This is evident in polling which shows that the importance which the public assigns to restoring the Chesapeake is as high in headwater regions as it is on the Bay front.

- The public's attitudes about the Bay, coupled with the educational and economic status of the region, creates a condition in which there is strong public support for Bay restoration. For example, the Chesapeake Bay Foundation has over 84,000 dues paying members.

- There is a voluminous flow of information about the Bay, both in the popular media and via other periodicals such as the widely distributed *Bay Journal*.

- The Chesapeake has received national attention, but although there have been some advantages to proximity to the nation's capital in garnering federal support, this has been, in my opinion, less important than those who envy our progress in the Chesapeake think.

- Certainly, these conditions do not always exist in other areas which are experiencing eutrophication, such as the northern Gulf or Mexico. Nonetheless, my observations of how the seven key questions have been addressed in the Chesapeake do, hopefully, suggest some focal points and shortcuts toward resolution of issues and development of effective solutions for the deleterious effects of coastal eutrophication.

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