Estuaries Vol. 26, No. 2A, p. 171–185 April 2003

A Watershed Perspective on Nutrient Enrichment, Science, and Policy in the Patuxent River, Maryland: 1960–2000†

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ABSTRACT: The Patuxent River, Maryland, is a nutrient-overenriched tributary of the Chesapeake Bay. Nutrient inputs from sewage outfalls and nonpoint sources (NPS) have grown substantially during the last four decades, and chlorophyll *a* levels have increased markedly with concomitant reductions in water quality and dissolved oxygen concentrations. The Patuxent has gained national attention because it was one of the first river basins in the U.S. for which basin-wide nutrient control standards were developed. These included a reduction in NPS inputs and a limit on both nitrogen (N) and phosphorus (P) loadings in sewage discharges intended to return the river to 1950s conditions. Full implementation of point source controls occurred by 1994, but population growth and land-use changes continue to increase total nutrient loadings to the river. The present paper provides the perspectives of scientists who participated in studies of the Patuxent River and its estuary over the last three decades, and who interacted with policy makers as decisions were made to develop a dual nutrient control strategy. Although nutrient control measures have not yet resulted in dramatic increases in water quality, we believe that without them, more extensive declines in water quality would have occurred. Future reductions will have to come from more effective NPS controls since future point source loadings will be difficult to further reduce with present technology. Changing land use will present a challenge to policy makers faced with sprawling population growth and accelerated deforestation.

"*How the land is used is a basic factor in the ecological health of the Chesapeake Bay.*" Year 2020 Panel Report, 1988

Introduction

In terms of its size and flow, and in comparison with other tributaries of the Chesapeake Bay, the Patuxent River is quite unremarkable. The Patuxent ranks only seventh in freshwater flow to the Bay proper and is dwarfed in comparison with its nearest neighbor to the south, the Potomac, which itself is considerably smaller than the northernmost and largest of all of the Chesapeake's tributaries, the Susquehanna. In earlier times, there was an appreciable yield of fish and shellfish from the Patuxent River, although its harvest still represented but a small portion of the yield of the full Chesapeake estuarine system (Maryland Department of Natural Resources 1989). Yet, in many ways, the Patuxent looms larger than its better-known counterparts. It exemplifies a river and estuary for which there has been a clear public recognition that excessive nutrient enrichment from upstream sources has had substantial effects on living resources in its estuarine reaches. The Patuxent has also been a site of particularly active research programs and for which there is one of the longest environmental data records for dissolved oxygen (DO), turbidity, sea grasses, and nutrient concentrations. There are two research institutions on the shores of the Patuxent that have been conducting studies on the river and estuary for decades (Chesapeake Biological Laboratory [CBL] and Academy of Natural Science Estuarine Research Center [ANSERC]), and there is also a substantial historical record of data that precedes the time of nutrient enrichment and extends through the period of greatest change. The Patuxent has garnered considerable legislative and regulatory attention because of its location adjacent to the nation's capital; that, in turn, has affected the role of the Patuxent debate in altering public policy. The entire basin is within one state, which simplifies, but does not eliminate jurisdictional complications.

During the late 1970s and early 1980s—a time when environmental changes in the Chesapeake gained national attention—the Patuxent was

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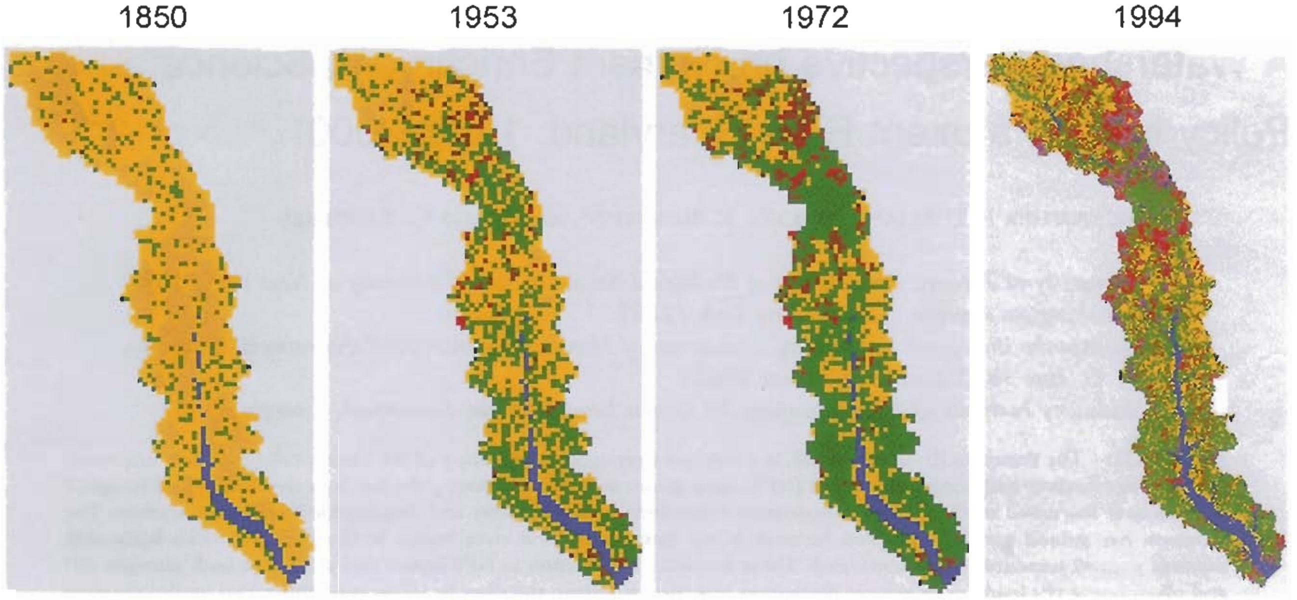
† This paper is dedicated to the memory of Dr. Donald R. Heinle who really started this investigation.



		1850	1953	1972	1994
Forest	🟩	14.3	37.3	57.0	51.6
Residential	🟫	0.3	4.6	8.0	15.5
Urban	🟥	0.0	1.2	2.3	4.3
Agro	🟨	85.5	57.0	32.8	28.5

Fig. 1. A time series of land use maps for the Patuxent River basin (1850, 1953, 1972, 1994). Maps were adapted from Voinov (2001). Values are percents of total area.

deemed by many as the State of Maryland's most prominent environmental concern. Water clarity decreased, once abundant sea grasses all but disappeared, and commercial fisheries declined. The Patuxent became a symbol of a perceived decline in environmental quality and an important driver of public policy for nutrient management in the Bay. After federal and state investments totaling millions to upgrade sewage treatment facilities in the 1980s and 1990s were completed, there were still questions about the policies and practices adopted for the Patuxent: how successful were they in achieving their intended goals?

We review four decades of change, 1960–2000, in the environmental quality and science-based policy for this river and estuary. Although the full 1960–2000 time frame will be discussed, most of the focus will be on the late 1970s and early 1980s, when fundamental science played a large role in policy decisions. The turbulent but important years are documented during which environmental awareness, science, and policy were all debated and formulated together. By focusing on several key policy-related events of the early 1980s, we chronicle concomitant developments in science and public policy that have enabled better responsiveness to environmental stresses in the region.

While Malone et al. (1993) documented key events in public policy that pertained to the Chesapeake Bay, the work reported here amplifies those events that are relevant to the Patuxent. Additional information on public policy and the Chesapeake Bay include Powers (1986) and D'Elia and Sanders (1987).

Demography and Land Use

Demography and land use are without question the driving factors of water quality in the Chesapeake and its tributaries (Year 2020 Panel Report 1988), particularly because of their influence on nutrient and sediment loading rates. Striking changes in land use have occurred in the Patuxent Basin over the last 150 years (Fig. 1). In colonial times, as was characteristic of much of the mid-Atlantic and northeastern U.S., the Patuxent watershed underwent widespread deforestation for agricultural purposes. By the middle of the 19th century, over 85% of the forest had been cut down, and the majority of the land was dedicated to agricultural uses (Fig. 1). Historical records and pa-

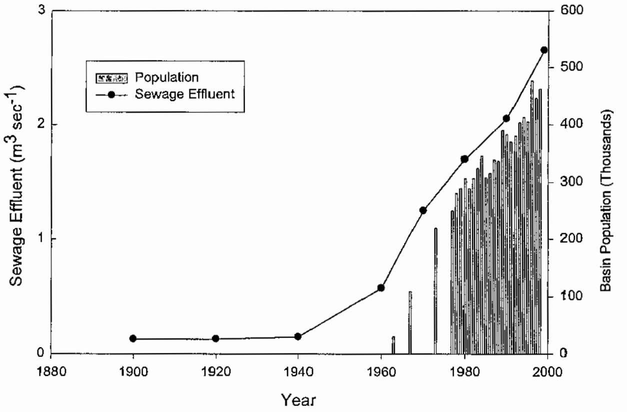


Fig. 2. Population and sewage effluent trends in the Patuxent River basin (1900–1999). Data are from Maryland Office of Planning (2001).

leoecological studies indicate very high rates of sedimentation beginning in the early 19th century (Kahn and Brush 1994).

By the middle of the 20th century, with the demographic shifts from rural areas to industrialized cities, much of the agricultural use had declined. Considerable reforestation occurred during the first half of the 20th century. Development of suburban and rural areas between Baltimore, Maryland, and Washington, D.C. was rapid and extensive during the post-World War II period. The rural electrification of the 1930s; the rise of the nation's capital as a seat of power and wealth, and as a commercial and cultural center; the development of improved federal and state highway systems; the development of disposable wealth and other factors; all contributed to a greater accessibility to agricultural or undeveloped areas. Together these factors set the stage for one of the fastest rates of growth that any area of the U.S. has experienced (Culliton et al. 1990). Before the 1960s, when the basin was predominantly rural and agricultural, basin population was less than 25,000. By the early 1960s, population growth began to accelerate at a rate that continues unabated to the present (Fig. 2).

The population growth of the 1960s required more public infrastructure, and there was considerable focus on developing sewage treatment plant facilities (STPs) in the more populated parts of the basin (Fig. 3). The links between the two are clear and obvious. Figure 2 also shows the rapid growth of sewage treatment effluent that accompanied population growth. In addition to adding new treatment capacity for new housing, existing housing was also being gradually converted from septic service to public sewerage.

During the 1950s, only about 60% of the land

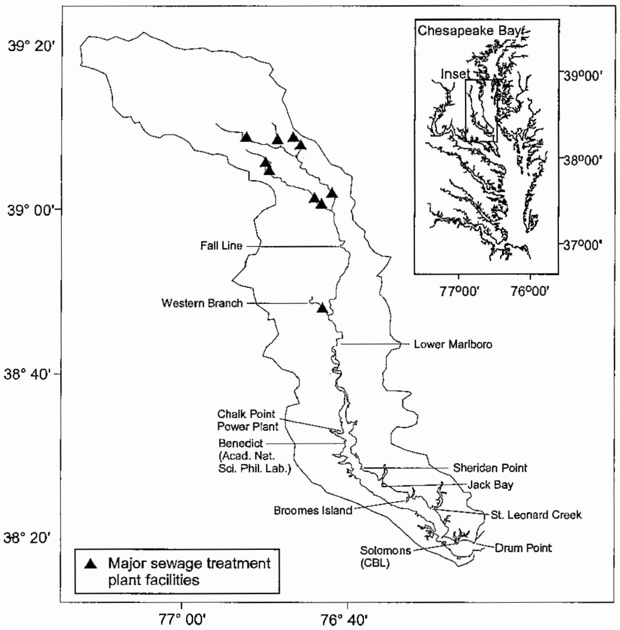


Fig. 3. A simple map of the Patuxent River drainage basin, river, and estuary. Sites mentioned in the text are labeled on this diagram. Major sewage treatment plant facilities are also indicated.

was used for agricultural purposes with most of the remainder being forested. Residential and urban uses increased from negligible (0.3%) in the 1850s to approximately 6% by 1953. The growth of residential and urban centers notwithstanding, by the end of the 1960s, the Patuxent watershed forest achieved nearly 60% coverage (Fig. 1) because of decreasing agricultural uses.

Since nonpoint sources (NPS) of nutrient loadings are higher in clear-cut forested and agricultural settings, land use undoubtedly had an effect on nutrient inputs to the river prior to the 20th century, in comparison with the environmental conditions prior to European colonization. Given that fertilizer applications were not substantial until the latter half of the 20th century, agricultural nutrient inputs from runoff prior to 1900 are not believed to be large in comparison with present day practices, and from the work of Brush (1984a,b) it appears that river and estuarine areas did not exhibit nutrient-enriched characteristics.

Rapid rates of population growth and changing land use have continued into the 1990s. The first half of the 20th century was characterized by a relatively constant population below 25,000, followed by abrupt changes that began in the 1960s yielding a current basin population of about 536,000 inhabitants. This represents a twenty-fold increase in population in just four decades. Although agricultural use of land continued to decline, forestation peaked in the early 1980s and has been declining since. By 1994, only 50% of the land area was forested, while there was a striking increase in residential and urban uses. In just two decades the Patuxent basin has become almost 20% residential and urban. The counties between, and to the south of Washington, D.C., and Baltimore, Maryland, were becoming bedroom communities for those cities. These changes all affected nutrient loading to the Patuxent River and estuary.

The 2020 Report (Year 2020 Panel Report 1988) to the Chesapeake Executive Council was a landmark assessment of the demographic problems facing the Bay and its watershed and underscored the importance of land use changes. Any statements applied broadly to the entire Chesapeake watershed when this report was published applied all the more to the Patuxent Basin which was experiencing even faster population growth and land use change. According to the report (p. 29), "The entire Chesapeake basin population grew almost 50% between 1950 and 1980 [while] the amount of land used for residential and commercial purposes increased 180%." Given that the Bay's watershed constituted one of the fastest growing areas of the nation during 1950–1980, the Patuxent's problems were further amplified. According to the report (p. 29), "undeveloped land has been converted to developed land at a rate that exceeds the rate of population growth." The report was clear in its diagnosis of the cause of the Bay's maladies in 1988 (p. 36), "More than any single development factor, we were concerned with low density sprawl." It was also blunt in its prescription for a cure (p. 45), "States must take the lead to establish and implement policies and programs that result in compact and efficient growth patterns."

The Role of Science and Public Awareness

Prior to the 1960s, Bay watermen and others felt that the Chesapeake and its tributaries offered limitless bounty in fish and shellfish harvests. There was little public recognition of over-harvesting or water quality changes although there were squabbles over whose right it was to partake of estuarine production. Even as late as the 1970s, natural resource management officials were still reinforcing the perception that all was well (e.g., Chesapeake Research Consortium 1977).

Despite a lack of public awareness during the early 1960s of limits to Bay production or assimilative capacity for increasing nutrient loads, scientific interest in the biology and ecology of key Bay species fortunately resulted in the expansion of several modest research laboratories. These facilities have played important roles in providing the information that has raised public concerns about the Bay's condition. The first of these facilities, CBL, located near the mouth of the Patuxent River, was established in the mid-1920s by Dr. Reginald V. Truitt, a faculty member of the University of Maryland. CBL scientists undertook many of the earliest published studies on estuarine nutrient and oxygen dynamics (e.g., Newcombe and Brust 1940; Nash 1947) that now provide important baseline information about the Bay prior to the 1960s when larger, publicly funded, monitoring and research programs began to be established. Given CBL's location at the mouth of the Patuxent River, there was particular emphasis on the study of the Patuxent itself, some of which was published but most of which remained as unpublished data in laboratory and field notebooks of researchers.

Many of the original notebooks were preserved in boxes in the library attic of CBL. In the early 1970s, CBL Professor Donald R. Heinle recognized the value of these unpublished historical data in establishing a scientifically documented case for environmental change in the Chesapeake system. Dr. Heinle began to summarize this information. He found that turbidity levels had increased markedly during the period 1940–1970. Concomitant with that change were alarming decreases in sea grass distribution and abundance, decreases in deep water oxygen concentrations, and an increase in nutrient levels, all of which Dr. Heinle deemed to be signs of nutrient enrichment. With this information in hand, he approached Dr. L. Eugene Cronin, former CBL Director, and then Director of the Chesapeake Research Consortium in Annapolis, Maryland. Dr. Cronin, himself a longtime student of the Bay, had his own concerns about declining water quality in the Bay. Dr. Cronin, in turn, briefed U.S. Senator Charles Mathias, who arranged for federal appropriations to be made to undertake the first studies under the aegis of the U.S. Environmental Protection Agency (USEPA) Chesapeake Bay Program. This funding enabled Heinle et al. (1980) to conduct a major review of historical data for the entire Bay system that established a sound scientific case that water quality had declined prior to and during the 1970s.

In the early 1960s, ANSERC, which had considerable interest in the effects of power plant siting and operation on estuaries, established a laboratory on the Patuxent River estuary at Benedict, Maryland. Through its studies of the Chalk Point Power Plant at Benedict, Maryland (Fig. 3), as well as studies of living resources in the river, this laboratory also contributed to an unusually rich historical record. This information proved to be enormously important in determining the extent of change that occurred in the post-1960 era. ANSERC moved to a new facility further down the

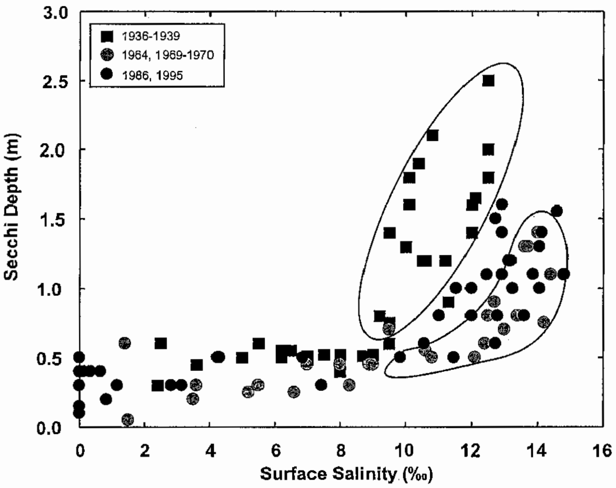


Fig. 4. Summer (July) Secchi depth measurements from data collected between 1936 and 1995 displayed as a function of salinity for the oligohaline and mesohaline regions of the Patuxent River estuary. Encircled data indicate Secchi depths in the early and more recent periods in the mesohaline portion of the estuary. This figure was adapted from Heinle et al. (1980). Data from the 1985–1995 period are from the Maryland Department of Natural Resources (2001).

estuary in the 1990s and staff continues to examine estuarine questions.

1930s to 1980s: Change and Recognition

Our understanding of the changes in water quality in the river and estuary from the mid-1930s to the mid-1960s is based largely on less than complete evidence. It is generally agreed that significant changes in the trophic structure and water quality of the Patuxent began to change markedly during this period. By far the most thorough information is from the synthesis study by Heinle et al. (1980). Of all the data available to these authors, none were as reliable as a time series of Secchi depth. Although Secchi depth becomes less precise in very turbid conditions, particularly below penetration depths less than 1 m or when particle sizes change with time in the water, Secchi measurements enable discrimination of turbidity levels due to phytoplankton concentrations in waters such as in the lower Patuxent estuary. Most of the lower 30 km of the river could be readily evaluated for differences in measurements taken from the 1930s through the late 1970s.

The Heinle et al. (1980) Secchi depth data are displayed along with more recent observations, as a function of salinity, in Fig. 4. The authors concluded that the lower Patuxent estuary was substantially more turbid in the 1970s that it had been 40 years before. There appear to be two possible explanations for this pattern. The first is that loadings of inert particulates had either increased or particle size had decreased substantially resulting in increased turbidity. Such loading changes presumably could have been from nonpoint source increases due to land-use changes, particularly in the upper portion of the basin. The other alternative, which seemed far more plausible to Heinle et al. (1980), was that phytoplankton concentrations in the river had increased substantially over that time. Two lines of evidence support such a hypothesis: increases in nutrient concentrations led to increases in phytoplankton production and biomass, and phytoplankton production increased secondary production or, more likely, sank to deeper waters and decayed and, because of microbial decomposition, oxygen concentrations were depleted. Indeed, phosphate concentrations increased in both the riverine and estuarine portions of the Patuxent from the late-1930s to the mid-1970s (Fig. 5). Furthermore, DO concentrations at depth were substantially lower in the 1970s than recorded four decades earlier (Fig. 6).

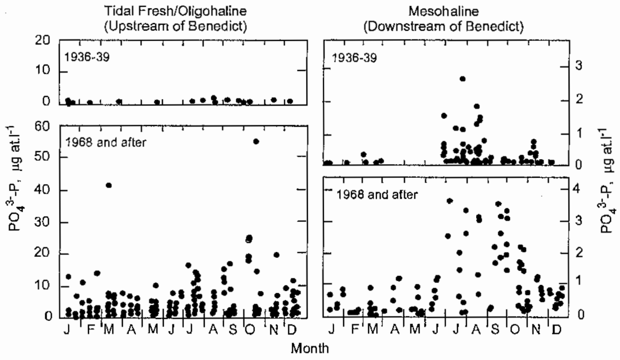


Fig. 5. Dissolved inorganic phosphorus concentrations from two time periods (1936–1939 and after 1969) and two regions (tidal fresh/oligohaline areas upstream and mesohaline area downstream of Benedict, Maryland) of the Patuxent River estuary. Note different scales of left and right panels. This figure was redrafted from Heinle et al. (1980).

While evidence accumulated that the trophic status of the Patuxent was rapidly changing by the 1970s, it was also becoming clear that living resources were being affected (Heinle et al. 1980). In the Patuxent, probably the best overall proxies for the state of living resources are sea grass densities (discussed elsewhere in this volume) and oyster harvest, the latter being something that is well known from Department of Natural Resources (DNR) records. Since the 1960s there have been studies conducted in the Patuxent and elsewhere to determine the condition of oysters in the estuary (e.g., Roosenburg 1969; Riedel et al. 1995). By the late 1970s, virtually everyone recognized the critical condition of the oyster fishery in the estuary. Not only had harvests decreased dramatically, but there was also evidence that oyster diseases,

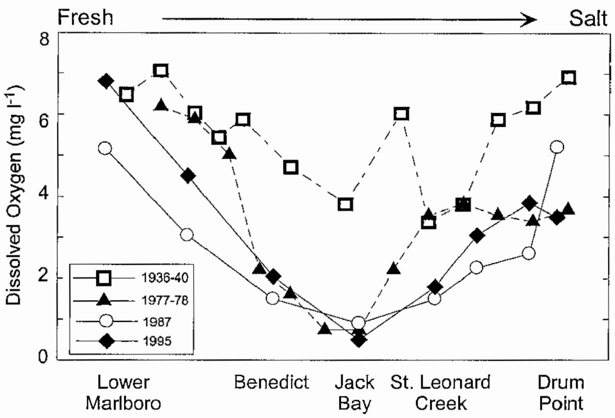


Fig. 6. Summer (July) dissolved oxygen concentrations in bottom waters of the Patuxent River estuary from tidal fresh regions (Lower Marlboro) to the junction of the estuary with Chesapeake Bay (Drum Point). The distance between the upper and lower stations is about 50 km. Data from 1936–1940 and 1977–1978 are from Heinle et al. (1980); data from 1987 and 1995 are from Maryland Department of Natural Resources (2001). Heinle et al. (1980) found about 77 summer season bottom DO measurements from the 1936–1940 period. Salinity values for the 1936–1940 period were within the range of more contemporary values indicating that the DO measurements observed during 1936–1940 were not the result of extreme hydrologic events. Locations are shown in Fig. 3.

particularly Dermo (Abbe et al. 2002), were increasing in the oysters left unharvested. The end of the 1970s saw considerable uncertainty about the proximate causes of the changes that were now being scientifically documented. The State of Maryland and the USEPA at times seemed oblivious that any change was occurring (Chesapeake Research Consortium 1977). By the end of the 1970s, after a successful lawsuit by the three southern Maryland counties against the more northern counties, the State of Maryland and USEPA acknowledged that change had occurred. A great debate emerged at this time throughout the Bay whether commercial over-harvesting, shellfish disease, increased sewage loading, declining water quality, or a combination of these were responsible for the irrefutable bad news about the status of the oyster fishery. There was much finger pointing, but little action on any front.

With the advent of powerful computers and simulation software, numerical modeling of water bodies gained considerable credibility and attention in the early 1970s. The newness of this space-age technology, as well as the apparent unambiguity and decisiveness of the results produced by models, led many policy makers to accept the results without question. By present standards, the computers used and the two-dimensional, steady-state models developed were unsophisticated relative to the task (HydroQual 1981). Even more significant though, the conceptual understanding behind the models was incomplete or flawed. In the 1970s some of the most debated causes of declining water quality related to the role of the benthos, the relative roles of point and nonpoint nutrient sources to rivers and estuaries, the relative importance of nitrogen (N) and phosphorus (P) as limiting nutrients in rivers and estuaries, and the influence of trophic structure on the expression of nutrient enrichment. None of these conceptual, scientific issues were close to resolution in the 1970s, and they were not incorporated into the computer models of the day. The result was that the computer models were seriously flawed and incapable of providing adequate projections of water quality under different management alternatives.

Although funding was available to study these conceptual issues, it was not sufficient and was rarely supplied by the agencies responsible for making key management decisions. Creative use of funding was necessary to enable fundamental studies of estuarine processes. For example, one of the authors (W. R. Boynton) initiated studies of benthic oxygen demand and nutrient regeneration in estuaries using funding directed at power plant impacts because no other federal or state agency had provided support for these studies. The other authors used funding from county governments to pursue issues related to nutrient limitation.

Environmental awareness grew in the 1960s and with it developed a national interest in passing landmark federal legislation in the early 1970s that would have broad implications in the study, understanding, and policy development for the Patuxent Basin. Undoubtedly the most relevant of this legislation was the 1972 Federal Water Pollution Control Act (PL 92–500), later referred to as the Clean Water Act. Several provisions of this legislation had particular relevance, namely §208, which mandated the formation of basin-wide wastewater treatment management, and §316, which dealt with power plant impacts. Although the original legislation was overly ambitious and not easily implemented, in our view, these provisions did result in increased scrutiny of the Patuxent's degrading water quality and led ultimately to research that identified nutrient enrichment as the leading cause for concern.

As chair of the Technical Advisory Committee advising the State of Maryland in the development of the §208 Basin Plan in the late 1970s, Dr. Heinle had a unique opportunity to work with Maryland DNR officials as they determined the course of action they would take for wastewater management in the basin (the 1972 legislation did not provide for NPS management). He was aware of the work of Ryther and Dunstan (1972) and others that suggested that the role of N as a limiting nutrient deserved more attention; this was one of the key breakthroughs in understanding coastal and estuarine eutrophication. Yet the State of Maryland's plan called only for P control. Dr. Heinle's suggestion that N removal be considered through advanced wastewater treatment processes met with considerable resistance from both DNR and USEPA, which were at the time committed to P removal nationwide.

In 1976, the three counties in southern Maryland were increasingly aware of the rapidly increasing sewage load to the river, declining water quality, loss of sea grasses, and decreasing oyster and fish harvests. Ultimately, the southern counties sued the upriver counties, the State of Maryland, and the USEPA to prevent further development and wastewater discharges. Taken together, the controversy over the rapid increase in sewage discharges and concern over the state's failure to provide for N removal and the lawsuit led to very acrimonious relationships among the regulatory agencies, citizen advocacy organizations, the southern Maryland counties, and the scientific community.

1980s—Diagnosis and Prescription

Monitoring data from the 1980s continued to show severe declines in water quality and living resources in some areas and continued poor conditions in others. For the Patuxent, there was the grim picture of a disappearing oyster industry and the near-elimination of sea grasses as the waters were becoming increasingly turbid and unattractive (Stankelis et al. 2003).

Ryther and Dunstan's (1972) seminal paper led other scientists to investigate the possibility that N was an important limiting nutrient in other coastal areas. While Dr. Heinle was the first to propose this for the Patuxent River, there was no funding to support studies to examine the issue in more detail; he and his colleagues had to use indirect evidence to support their contention (i.e., examination of N:P ratios and nutrient concentrations). The computer models of the 1970s had led the State of Maryland and USEPA to believe that P was the single limiting nutrient and if controlled in sewage effluent, would lead to substantial improvements in water quality. The models were constructed to make this inevitable under most scenarios. Sanitary engineers emphasized that if a nutrient element, either N or P, were to be removed via an advanced wastewater treatment (AWT) process, it should be P, because it was much less expensive and easier to do. Academic scientists were skeptical that the role of N could be so easily dismissed—it appeared that the underlying factor driving policy towards P removal was lower cost.

In 1980, Maryland Governor Harry Hughes recognized the controversial role of the DNR in Patuxent decision making and he determined that authority to deal with water quality issues should rest instead in the newly created Office of Environmental Programs (OEP) in the Maryland Department of Health and Mental Hygiene (DHMH). Governor Hughes hired a young lawyer, William E. Eichbaum, as assistant secretary to head this newly formed department, which was staffed primarily with State of Maryland sanitary engineers familiar with Patuxent water quality issues and with biases towards the P removal position adopted by DNR. The reorganization was a pivotal event and the selection of Eichbaum had a profound effect on the future of sewage treatment decision making for this river and estuary and ultimately, we think, on national policy.

One of Eichbaum's first acts was to tour the Patuxent Basin and meet with public officials, scientists, and interested citizens to gain a clear perspective of the problem. Eichbaum made a concerted effort to understand the complex scientific issues involved, and he quickly realized that there would be endless litigation unless he could somehow bring the parties together, including several estuarine scientists, to develop a compromise. Accordingly, he brought 30 key players together for three intensive days (December 2–4, 1981) of closed discussion and negotiation in a professionally mediated format. Two of the authors (C. F. D'Elia and W. R. Boynton) of this paper attended the charrette, and, as it turned out, played useful roles in the outcome of the negotiations, particularly as they related to the issue of N loading rates.

The charrette would turn out to be a remarkable event in the environmental history of the Patuxent, and indeed of the Chesapeake itself, for several reasons. It marked the first time that a consensus was reached on nutrient inputs for a tributary based on desired water quality outcomes and defined nutrient inputs. This implied that a clear linkage exists between the two and presaged the Total Maximum Daily Load (TMDL) approach now mandated throughout the Chesapeake and the U.S. It also was the first recognition by public officials from state and county agencies that N was indeed a key problem to be resolved, and it involved the acceptance by the State of Maryland of its own increased responsibility to meet the needs of AWT without federal cost sharing.

During the first day of the charrette, there were presentations by technical people. One of the key understandings Eichbaum had with all Charette attendees was that both sides needed to recognize and state clearly their positions and expectations for successful negotiations. Officials from Howard County, who had instituted state-of-the-art chemical P removal, insisted that they had done their part already and that they should not be expected to do more. Officials of the three southern counties, represented by the Tri-County Council for Southern Maryland, took the position, given the scientific perspectives held by estuarine scientists involved, that N removal was required to make substantial improvement in the lower, estuarine part of the river. State Senator C. Bernard Fowler, the leader of the Southern Maryland delegation, was particularly influential in that he was able to recount his personal experiences of the striking decline of water quality in the Patuxent. Wading waist deep in the river at Broome's Island during the 1950s, a time during which large harvests of fish and shellfish were common in this section of the river, Fowler could see his feet. That was no longer the case in 1980. He started an annual event in which citizens wade into the water to see if there is any change in water clarity (Horton 1993). Agreement was eventually reached on a key goal for the Patuxent of returning water quality conditions to those common during the 1950s.

The scientists present emphasized the value of establishing a clear definition of what would be achieved under conditions where nutrient loads were returned to the values of the 1950s. They recommended the designation of the Broome's Island-Sheridan Point areas as key areas to be expected to respond favorably to lower nutrient loadings. This section of the river had been, by the end of the 1970s, the location where chlorophyll *a* (chl *a*) values exceeded 50 $\mu g\ l^{-1}$ and where oxygen concentrations in sub-pycnoclinal waters were very hypoxic for four or more months each year. Figure 6 shows the historical changes in DO in the river at selected locations. Sheridan Point is very near Jack Bay, and the figure clearly indicates the profound changes in DO concentration observed in this area.

Another clear outcome of the charrette discussions was a consensus to focus on DO and chl *a* concentrations as proxies for water quality and ecosystem health. While these parameters are commonly used as proxies today, public officials and interested citizens, who at the time were new to the scientific concepts of nutrient enrichment, did not know what indicators were best for measuring improvements in the Patuxent. Recognition that chl *a* and DO concentrations were good choices for this was an important development in the history of the much larger Chesapeake Bay Program water quality monitoring effort.

Although it was not common practice at the time, the charrette recommended that the State of Maryland establish a loading standard for the Patuxent, similar to the TMDL approach used today. Effluent standards at that time were strictly concentration based. The decision was made to establish a loading limit that approximated that of the 1950s, which reflected the environmental quality targeted for the entire river. The original nutrient load estimates suggested that the 1950s N and P loads were approximately 40% of those in 1980, a percentage very similar to that adopted Bay-wide in 1987. While these estimates were preliminary, in some instances, they were adopted as a goal.

Dr. Heinle left the state before the charrette, but he had played a significant role prior to the charrette at raising awareness about the probable controlling role of N as a limiting nutrient in the estuary, particularly the need to control N inputs in sewage effluents. No studies had been conducted locally to verify such a role for N, and federal policy at the time was very much opposed to undertaking either N removal or a dual nutrient control strategy. Accordingly, any statewide action to remove N from effluent would put federal cost sharing at risk. State and county authorities would have to bear the costs, which for N were substantial, because the primary option available was a chemically based (methanol) denitrification process that was very expensive in terms of implementation, operation, and management.

Neither the State nor the upstream counties were in favor of N removal, given the daunting cost considerations they were facing. The southern Maryland delegation remained staunch in its position that N removal must be implemented. The negotiations appeared to be in serious jeopardy, almost to the end of the charrette, when Washington Suburban Sanitary Commission head General McGeary, made a major concession that soon after appeared to have cost him his job. In short, he approved the conversion of the Western Branch STP to advanced wastewater treatment to remove N to the 5 mg l^{-1} level (pre-treatment concentrations ~ 20 mg l^{-1}).

Although the accord reached at the Patuxent charrette appeared to have represented a resolution including N control of STP effluents, both the State of Maryland and USEPA were reluctant to accept this agreement. They resisted further attempts by citizen activists to gain wider acceptance of N controls and continued to criticize the hypothesis that N was the growth-limiting nutrient element in the estuary. This controversy precipitated a 1983 legal challenge by Calvert County citizen activist, William Johnston, that resulted in an administrative law hearing on the N issue in the Patuxent. Johnston called 8 scientists as expert witnesses, including the authors of the present paper. His contention was that removing N would result in reduction in chl *a* levels and concomitant improvement of bottom-water DO concentrations. The State argued that removing N would simply promote N-fixation, which would nullify any improvement. The State also contended that it would be possible to remove P to such a low level that it would become limiting, in effect ignoring the contribution of sediment-derived P, which was known to be important (Boynton et al. 1980).

Although USEPA seemed unwilling to fund experimentation on N enrichment effects, and by doing so open the possibility that N removal would be substantiated, we were able to obtain funding to undertake such studies. The authors of the present paper proposed a series of mesocosm experiments to examine factors affecting phytoplankton growth and species composition in the river (D'Elia et al. 1986; Sanders et al. 1987). This experimental system had originally been developed to examine toxicant effects, but it was easily adapted to nutrient-enrichment experiments. Over objections of his staff, Eichbaum agreed to fund part of the microcosm work, which was also funded by FMC Corporation and Procter and Gamble, which had vested interests in the N versus P controversy because of their production of phosphate-based detergents and fertilizers, and by Maryland Sea Grant development funds and Calvert County, Maryland.

Industry funding can be controversial so a precondition of accepting the funding was that there could be no special demands placed on the investigators, who were free to publish results in the open literature (e.g., Sanders et al. 1987), and that OEP would review experimental protocols. A special feature of this effort was that Sander et al. were able to bring together a spectrum of funding sources (local, state, federal, and industry), the very groups who were on the opposite sides of legal and legislative issues. This was a remarkable example of science being brought to bear on a contentious legal and public policy issue.

The mesocosm experiments developed cogent evidence that N had a very strong role in promoting phytoplankton growth during the spring, summer, and fall seasons and responses to P-enrichment were weak and restricted to the winter (Fig. 7). Despite this strong scientific evidence to support the case for N removal, agency resistance to implementing it remained strong. Two breakthrough events occurred that caused reconsideration of both the federal and state opposition to N removal. First, the evolving sewage treatment technology developed a cost-effective alternative for N removal. The new Biological Nutrient Removal (BNR) process, championed by Virginia Polytechnic Institute and State University scientist and en-

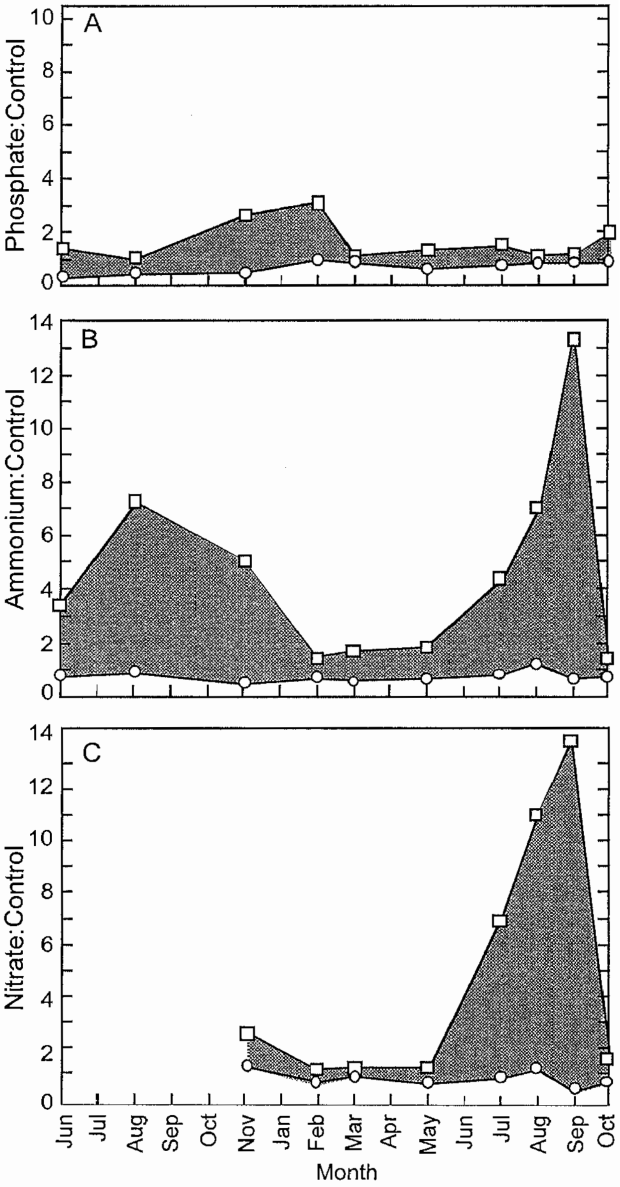


Fig. 7. Range of ratios of Relative Fluorescence Units (RFU, a proxy for chlorophyll *a* concentration) of triplicate nutrient-enriched experimental mesocosms (1 m^3) to mean of triplicate unenriched control mesocosms during each experiment from June 1983 through October 1984. (A) phosphate-enriched to control; (B) ammonium-enriched to control; (C) nitrate-enriched to control (nitrate enrichments were not done prior to November 1983). The greater the darkened portions of each panel, the greater the nutrient enrichment potential for a given nutrient. This figure was adapted from D'Elia et al. (1986).

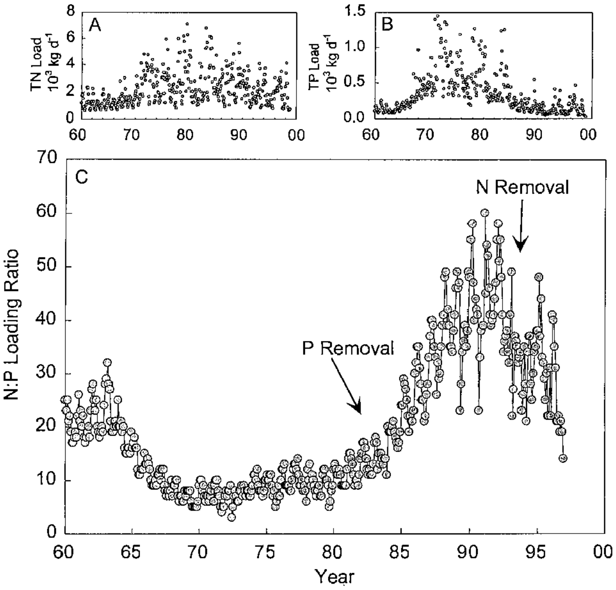


Fig. 8. A time series of average monthly A) total nitrogen (TN) and B) phosphorus (TP) loads at the fall line of the Patuxent River estuary from 1960 to 1999 and C) monthly average TN:TP ratios (molar basis) for nutrient inputs at the fall line of the Patuxent River estuary from 1960 to 1999. Loads from 1960 to 1977 were estimated by Hagy et al. (1998) and loads from 1978 to 1999 are from Langland et al. (2001).

gineer Clifford Randall, took advantage of the organic component of primary sewage liquor and the high biological oxygen demand in the secondary process to remove N through denitrification. In addition to its cost effectiveness from the operation and maintenance standpoint, this process required relatively little upgrading of existing facilities. Second, as Malone et al. (1993) have noted, another substantial breakthrough in the acceptance of the N hypothesis occurred in 1984 when the USEPA Chesapeake Bay Program Scientific and Technical Advisory Committee strongly endorsed N control. Taken together, these two actions caused a rapid change of both the USEPA (1986) and the State position on N control of sewage.

1990s—Action, Implementation, and Results

By the 1990s extensive monitoring and research data were available to allow for construction of comprehensive N and P budgets for the Patuxent, including a 40-year record of changes in nutrient inputs from point and nonpoint sources at the fall line (Fig. 8).

Available information concerning nutrient additions to the Patuxent River estuary, including those from point and nonpoint sources and from atmospheric deposition of N and P compounds directly to surface waters of the estuary, are summarized in Table 1. The geographic location of

TABLE 1. A summary of mean daily total nitrogen (TN) and phosphorus (TP) inputs (kg d^{-1}) to the Patuxent River estuary. Data and methodological details are provided in Boynton et al. (1995). Post-BNR point source data are from Wiedeman and Cosgrove (1998). Areal nutrient loads referred to in the text were computed using a total estuarine surface area of 137 × 10^6 m^2 (Cronin and Pritchard 1975).

	TN	TP
Point sources		
Pre-BNR above fall line	1,577	124
Pre-BNR below fall line	744	60
Post-BNR above fall line	744	57
Post-BNR below fall line	454	50
Nonpoint sources		
Above fall line	984	43
Below fall line	2,220	148
Direct atmospheric deposition	603	24
Pre-BNR total load (kg d^{-1})	6,128	399
Areal load (g N or P m^{-2} yr^{-1})	16	1.1

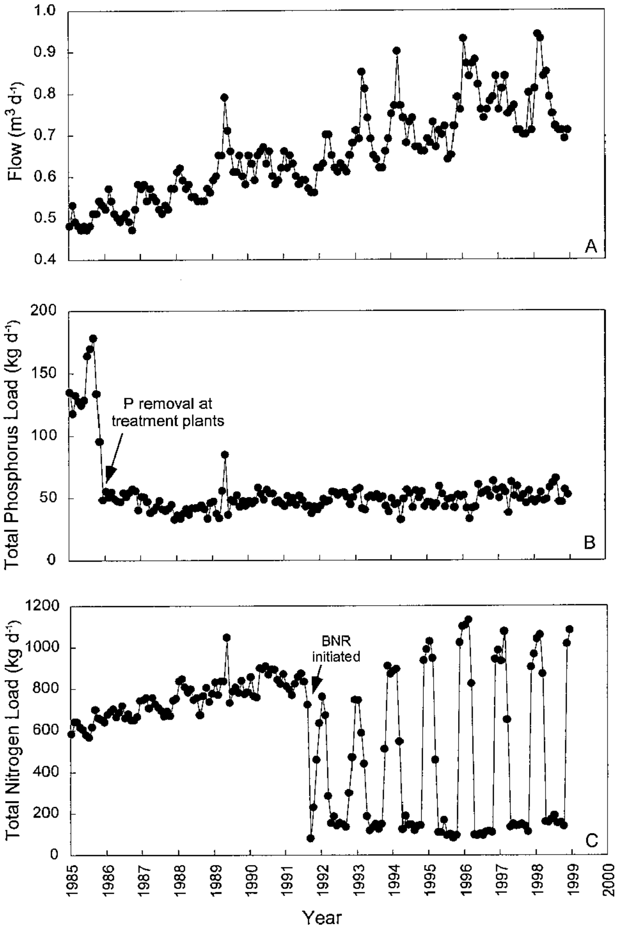


Fig. 9. Point source flow and loading from below the fall line: flow (A), total phosphorus (B), and total nitrogen (C).

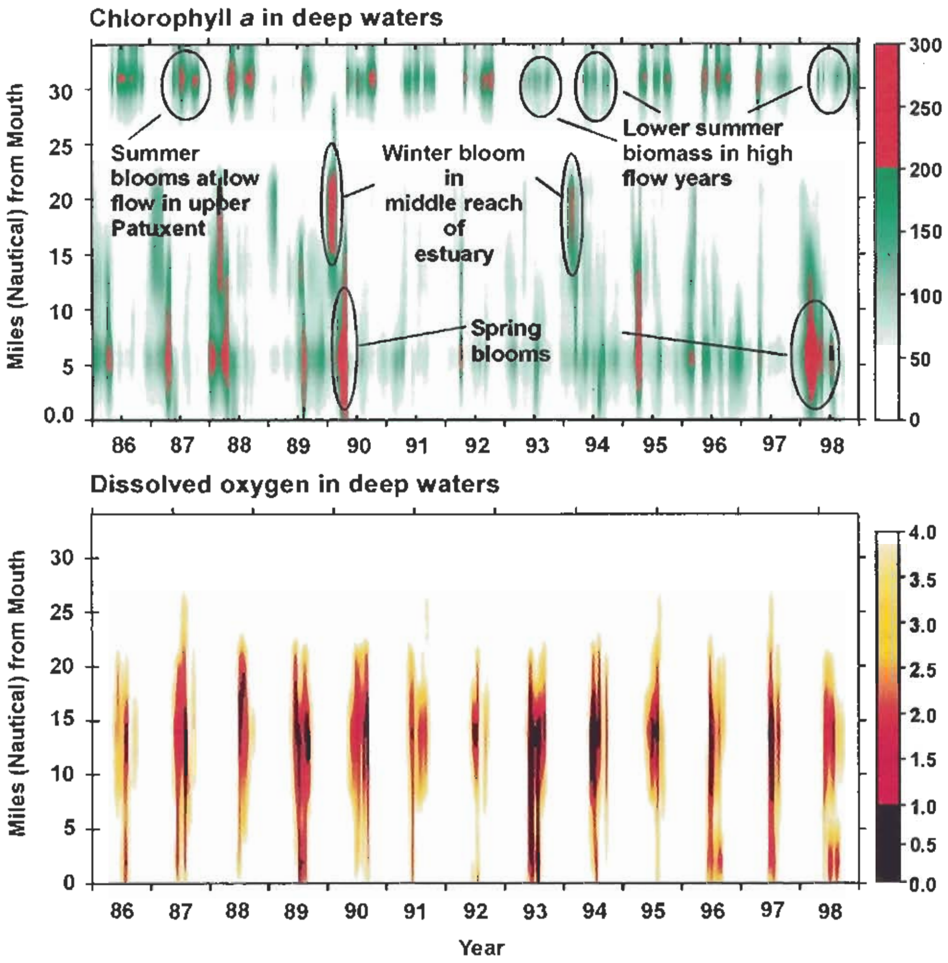


Fig. 10. A time-space plot of water column integrated chlorophyll *a* (mg m^{-2}) and dissolved oxygen conditions in deep waters (mg l^{-1}) of the Patuxent River estuary from 1986 through 1998. Data are from the Maryland Department of Natural Resources (2001); data were assembled by Hagy (personal communication).

sources according to position either above or below the Patuxent fall line are also indicated. The table compares mean point source loads during the 5-yr periods before (1985–1990) and after (1993–1998) BNR was fully implemented at STPs. Several interesting points emerged. N and P loading to the Patuxent estuary averaged about 16.0 and 1.1 g m^{-2} yr^{-1}, respectively. Relative to other estuarine systems in the U.S. and other areas of the world, these are moderate input rates. Systems such as Baltimore, Boston, and Tokyo Harbors, and the Potomac River estuary are far more heavily loaded with N and P, while many coastal lagoons and large enclosed seas, such as the Baltic, are less loaded than the Patuxent (Boynton et al. 1995). The Patuxent is not an extreme case, with respect to loading rates, though there have been and continue to be clear signs of the negative effects of nutrient enrichment with regard to chl *a* and DO. The Patuxent has been viewed by environmental management agencies as a point-source dominated ecosystem. As indicated in Table 1, point sources played an important role prior to BNR, representing about 38% of the total nitrogen (TN) load, but even during this period, point sources of TN did not dominate N loads. During the post-BNR period, point sources contributed about 20% of the load. Large reductions have been made in point source inputs but future significant reductions in the Patuxent, and in most Chesapeake Bay tributaries, will need to focus on the more difficult to control nonpoint and atmospheric sources of N (Boynton et al. 1995).

Fall line N and P load data also show the striking effects of land use, demographic change, and sewage control strategies (Hagy et al. 1998; Fig. 8). Clearly reflected is the effect of P removal from sewage in the early 1980s followed by the P ban in detergents in the mid-1980s. Trends in TN loading were not as dramatic and occurred later because

N removal from sewage was not fully implemented at the larger treatment plants until 1993.

The nutrient budget above the fall line is dramatically affected by sewage inputs, which are a major part of the allochthonous nutrient inputs. This conclusion, which is illustrated by the N:P loading ratios derived from the data shown in Fig. 8a,b, also demonstrates the profound effect that the sewage treatment processes had on the nature of the residual loads. As the input of untreated, P-rich sewage increased in the 1960s, N:P ratios dropped substantially, well below the Redfield ratios of 16:1 (Fig. 8c). These ratios can be misleading, since effective N:P delivery rates of allochthonous nutrients to plankton in the water column depend on seasonal differences in benthic exchanges and other processes (D'Elia et al. 1986). There was a dramatic reduction (~4 times) in total P loads following modifications of STPs to tertiary levels and the implementation of standards for low-P detergents. The N:P ratios increased to achieve a maximum of approximately 45:1, indicating an N-rich nutrient source. TN loads were also reduced in an even more dramatic fashion on a seasonal basis (~6 times) following adoption of BNR technologies. As N decreased, so did N:P ratios and by the mid-1990s, they were approximately at the Redfield ratio, similar to the ratio observed some 40 years earlier.

In as much as N is currently removed only during the warmer portions of the year (N-removal is temperature dependent), cool season loads are tending upward in response to increasing flows from treatment plants (Fig. 9a,c). Increasing discharges will erode progress made in controlling these point source inputs. If flows continue to increase, average annual TN loads in just a few more years will be about the same as they were in 1985, prior to initiation of major efforts to control point source discharges.

Although the effects of both point source P and N removal clearly affect the nutrient loading rates and the N:P ratio, unequivocal evidence of recovery in terms of improved water clarity, elimination of algal blooms, large decreases in hypoxic water volumes, or general recovery of sea grasses has yet to be recorded, especially in the mesohaline portions of the estuary.

Concentrations of chl *a* and DO in deep waters are two variables often used as indicators of nutrient enrichment in aquatic ecosystems. Beginning in 1986, the Chesapeake Bay Water Quality Monitoring Program began systematic measurements (bi-monthly measurement frequency at 10 stations along the axis of the estuary) and a reliable record of water quality during this period is now available. Chl *a* and DO data have been summarized in time-space plots (Fig. 10). Both regular patterns and interannual variability are evident in both plots. Spring blooms occur every year in the lower estuary but are much larger in high river flow years than in drought years. Summer accumulations of chl *a* occur in the upper reaches of the estuary, especially during dry summers when water residence times are longer than normal. Deep waters of the estuary have DO concentrations in excess of 4 mg l^{-1} during the cool periods of the year but hypoxia develops every year during the summer period. Hypoxic intensity, duration, and areal extent vary strongly among years with hypoxic characteristics being most intense during wet years when vertical stratification becomes greatest. We have emphasized in the above discussion the importance of nutrient additions originating from the land and atmosphere. These are not the only sources. Application of a box model developed for the Patuxent by Hagy et al. (2000) indicated that on an annual basis N and P was transported from the estuary to the Bay. During summer, inorganic N and P are imported from the Bay and contribute to poor water quality conditions during that portion of the year. It appears that nutrient input reductions from point and nonpoint sources have not yet been large enough to modify, in any large fashion, the patterns of water quality that have been well documented via the monitoring program. It also appears that larger reductions will be needed, especially in the nonpoint source category.

Future Prospects

Although nutrient control measures have not yet resulted in dramatic increases in water quality or restoration of living resources, unrelenting attention to reducing N and P inputs will be required to help offset the effects that would otherwise be experienced with population increases. Because water quality is better in low-load years (low flow years) than in high load years (high flow years; Fig. 10) additional nutrient decreases should help to improve water quality conditions. In this sense, significantly better NPS controls will be a key issue, as further reductions in point source loadings will not be as large or as cost-effectively achieved as in earlier periods.

Although progress has been made in mitigating the effects of population growth and concomitant land use changes, large NPS inputs still remain the greatest threats to the Patuxent and the Chesapeake Bay environmental quality. Serious NPS reduction programs are relatively new and there is a great deal of room for improvement and expansion of these efforts. There has also been increased interest and excitement in restoration of estuarine habitats known to exert positive effects on water quality (e.g., marshes, submerged aquatic vegetation, and oyster reefs). In our opinion, sustainable limits will be reached once all reasonable attempts made to further reduce nonpoint and point source inputs no longer result in salubrious changes to water quality. This will present policy makers with a considerable dilemma, because the main alternative available will be to prevent further net immigration to the area (and associated development), something that contravenes the fundamental freedoms Americans now have to choose where to live and how to use private lands.

Conclusions

Early in this paper the following question was posed: have the policies and practices adopted for the Patuxent been successful in achieving their intended goals? While there are signs of recovery on the horizon, it is still premature to state so unequivocally. It could take another 5 or even 10 years to see if the policies and practices adopted in the mid-1980s will ultimately achieve the stated goal of returning the Patuxent's water quality to that of four decades ago. In our view, the public and public officials must learn to accept that rapid solutions to environmental problems are rarely available. It can take as long or longer to solve an environmental problem as it took to cause it, and even then, given scientific uncertainties and other environmental changes that may be occurring (e.g., sea-level rise), solutions may be elusive.

Some unequivocal conclusions can be made now. One of the most important lessons of the Patuxent was the prominent role that science and scientifically driven monitoring programs have had in affecting policy making. The scientists who worked on and near the Patuxent played a large role in formulating the close connection that developed between state-of-the-art science and evolving public policy. During the critical period of time from the late 1970s through the mid 1980s many scientists had regular and intensive contact with elected and appointed State of Maryland and federal officials, non-government organizations, citizen groups, the press, and even the courts. These scientists were generally able to focus their advocacy on science and the application thereof to public policy rather than on given policy actions. This emphasis on science kept their credibility high with politicians and the public, but did not compromise the credibility of their research findings. Key individuals in the press (e.g., Tom Horton of the *Baltimore Sun*) did much to help interpret the science for the public, and abetted the efforts of scientists to get relevant research into the everyday dialogues of those public officials making key decisions for the Patuxent.

The Patuxent case study also shows how important the availability of high quality monitoring data and long records have proven to be in diagnosing problems, understanding the causes, and developing effective remediation strategies (Heinle et al. 1980; D'Elia et al. 1992). No less important has been the availability of adequate funding for scientific research. In this case, it largely resulted from the recognition of key officials, among them Assistant Secretary of OEP, DHMH William Eichbaum, State Senator C. Bernard Fowler, and U.S. Senator Charles Mathias, that scientific understanding was incomplete and that research could add a clearer understanding to the public dialogue. Their willingness to commit themselves to provide special funding for research on the Patuxent and Chesapeake was essential in making available the resources needed.

Another lesson of the Patuxent is that research on pollution abatement technology, such as BNR, can really pay off. Research into improving public works technology is supported at a fraction of what is done for industrial research and development efforts. This is very short-sighted.

While we recognize the need to keep management options as straightforward and cost-effective as possible, the rigid approach to implementing AWT protocols of the late 1970s and early 1980s needs to be avoided in the future. Fear of the costs of implementing N removal on the Patuxent and loss of federal matching funds led policy makers at the time to conclude, despite substantial scientific evidence to the contrary, that a less expensive P-removal strategy could be forced to work. Flexibility in defining standards and prescribing solutions is key to effective management of nutrient enrichment problems. Cost is always an issue, and ultimately the public must determine if the cost to undertake a scientifically sound remediation program is practical. If it is deemed not to be, other alternatives that are scientifically supportable must be sought, or the technology must be improved to make it more cost effective.

While it is premature to conclude that the N-removal strategy for the Patuxent has been successful in reversing the damage of four decades of excessive nutrient enrichment, it does appear that for the present, further degradation has abated. The next decade should provide the answer to the initial question unless population growth simply overwhelms the system. As the Year 2020 Panel Report (1988, p. 13) so correctly stated, "How the land is used is a basic factor in the ecological health of the Chesapeake Bay." That, in large measure, is a function of demography.

ACKNOWLEDGMENTS

The authors wish to thank a number of individuals and institutions for assistance without which this paper would not have been possible or as interesting to produce. We thank the USEPA supported Chesapeake Bay Program and the Ecosystem Processes Component of the Maryland Water Quality Monitoring Program for providing essential data, and Maryland Sea Grant College for critical support when it was most needed. Rob Magnien and Bruce Michael have been particularly helpful. James Hagy summarized large portions of the monitoring program data set, produced several summary diagrams and was very instrumental in reconstructing nutrient loads to the Patuxent prior to 1978. Dr. Frances Rohland provided very helpful editorial and graphics support, as well as timely encouragement.

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Received for consideration, December 3, 2001
Accepted for publication, April 5, 2002