TIDAL POTOMAC INTEGRATIVE ANALYSIS PROJECT

A Series of Reports on the Water Quality and Living Resources Responses
to Management Actions to Reduce Nutrients in the Potomac River Estuary

EXECUTIVE SUMMARY

Revised February, 2000

The Potomac River Estuary represents one of our nation's emerging success stories in water quality restoration. The estuary begins at the Piedmont fall-line in Washington, D.C. where it receives about 90% of its freshwater surface flow, and it travels 113 miles (182 kilometers) across the Mid-Atlantic Coastal Plain to the Chesapeake Bay. Historical accounts indicate the estuary was once a diverse, productive ecosystem and it yielded some of the largest United States East Coast fish harvests for many years in the 19th century. Over-harvested fisheries and water quality degradation began to emerge as problems about 150 years ago. Nutrient enrichment escalated sharply and spread downriver in the 20th century and the estuary was grossly polluted and considered a national disgrace by the 1960s, despite sporadic efforts to treat waste from the rapidly growing human population. Abundant nutrients, especially phosphorus, nitrogen, and organic matter, caused excessive algal growth, low dissolved oxygen levels and high turbidity.

Management Actions

The estuary condition stimulated management action and became a catalyst of the nation's Clean Water Act of 1972. Regional jurisdictions expanded and upgraded wastewater treatment facilities to reduce phosphorus and organic matter, and to convert ammonium nitrogen to less toxic nitrate. They implemented a ban on phosphate detergents, encouraged protection of wetlands and riparian buffers, advocated soil and runoff controls in the basin and established caps on nutrient loads. Recently, a new technology to remove nitrogen from wastewater was implemented at Blue Plains, the largest treatment plant in Washington, D.C. The impetus for many of these activities came from enforcement programs established as a result of the Potomac Washington Area Enforcement Conferences in 1957, 1958, and 1969 - 1970, from the National Pollutant Discharge Elimination System (NPDES) established in the early 1970s, and from a regional agreement signed by the Executive Council of the newly formed Chesapeake Bay Program (CBP) in 1983 which called for all levels of government to cooperatively reduce pollution in Chesapeake Bay tributaries, including the Potomac River. The Chesapeake Bay Agreement was updated in 1987 to include a 40% reduction goal in "controllable" nitrogen and phosphorus loadings from the tributaries by the year 2000. Over the past four decades, regional commitments have broadened from simply cleaning up the fouled waters of the Potomac Estuary, to restoring the potential of the estuary ecosystem to provide abundant food and habitat for fish and wildlife.

Report Objective

This report assesses the available Potomac monitoring data in order to a) quantify how anthropogenic nutrient reduction strategies have changed nutrient loads and altered water and habitat quality, and b) determine if key biological communities have responded positively to these changes. Emphasis was placed on trying to account for natural variability in the ecosystem caused by flow, season and salinity in order to identify changes that could be related to management actions. The authors calculated trends in nutrient loadings and ambient water quality for the "CBP Years" (i.e. 1985 - 1998) and for longer time periods. These trends were then compared to the status and trends of ecologically important groups, including underwater grasses, plankton and benthos. The authors attempted to answer two general questions: *Will the current nutrient reduction policies successfully return the Potomac water quality to desirable and habitable levels? Will current nutrient reductions sufficiently improve food and habitat conditions so that the impacts of other stressors–habitat loss, over-harvesting, exotic species, toxic pollutants--are overcome and a balanced, productive ecosystem with abundant fish and wildlife populations is restored?* The entire report consists of this synthesis of the project team's analyses, followed by detailed reports written by individual team members.

Pollutant Loads Delivered to the Estuary at the Fall-line

Surface freshwater flows ranging between 2.6 trillion and 24.9 trillion cubic meters per year enter the Potomac Estuary at the Piedmont fall-line. Annual pollutant loads delivered to the estuary at the fall-line are directly related to the amount of freshwater discharged each year and the pollutant concentrations in the water. Daily flow rates and pollutant concentrations measured near the fall-line were used to generate estimates of actual fall-line loads. Trends in major landscape inputs were also used to infer historical fall-line loads.

Long-term Perspective

Measured and inferred 20th century increases in fall-line loads of sediment and nutrients reflect changing land uses in the upper basin, including a 3-fold population increase to 16.6 people/km^2, major shifts in agricultural practices, increased meat and poultry production, and increased atmospheric deposition. Estimated landscape inputs from wastewater, agriculture and atmospheric deposition alone suggest total phosphorus loads at the fall-line rose at least 6-fold and total nitrogen loads rose at least 5-fold between 1900 and the mid-1980s. Actual water quality measurements made near the fall-line show a comparable 5-fold rise in the concentration of nitrate (a component of total nitrogen) since 1913. Total residue (a measure of dissolved and particulate matter) and sulfate loads doubled, potassium and chloride loads rose 10-fold, and water became more alkaline in the same period.

CBP Years

A close succession of wet years in 1993, 1994, 1996 and 1998 caused a 71% rising trend in Potomac fall-line freshwater flow during the "CBP Years," from 1985 to 1998, and offset stable or improving trends in fall-line pollutant concentrations and loadings. Trends in total nitrogen (TN) and nitrate-nitrite (NOx) loadings increased significantly when they might have remained unchanged in an average-flow period, and trends in sediments, total phosphorus (TP) and dissolved inorganic phosphorus (DIP) loadings remained unchanged when they might have decreased (Figure 1). A return to more average flows should produce lower sediment and phosphorus loads. Annual average loading rates ranged from about 42,000 to 171,000 kilograms TN per day and from 2,000 to 19,400 kilograms TP per day in the CBP Years. The large % change in NOx fall-line loadings (Figure 1) indicates nitrogen composition is shifting towards a higher proportion of NOx, possibly the result of nitrification at upriver treatment plants. Downward trends (~35%) in fall-line concentrations of ammonia and organic nitrogen compounds support this suggestion.

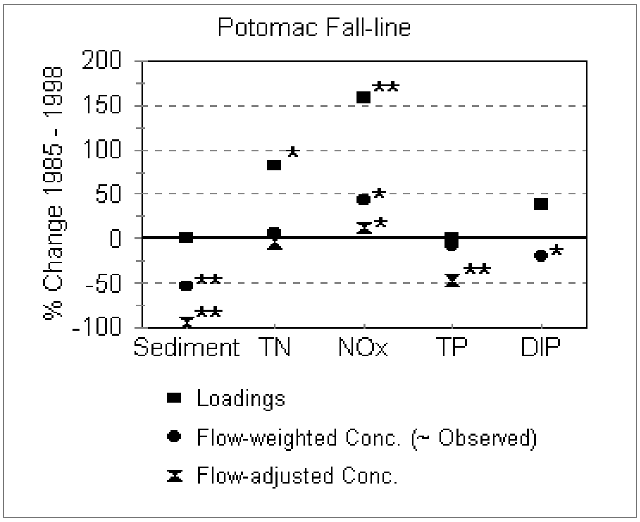

Figure 1. Comparison of % change in sediment, total nitrogen (TN), nitrate-nitrite (NOx), total phosphorus (TP) and dissolved inorganic nitrogen (DIP) at the Potomac fall-line station for the Chesapeake Bay Program years, 1985 - 1998. Freshwater flow at the fall-line increased 71% due to a close succession of wet years in 1993, 1994, 1996 and 1998 and offset improvements occurring in sediment and phosphorus concentrations and loadings. Loadings = total quantity entering tidal waters annually at the fall-line; flow-weighted concentration = concentration not adjusted for flow effects (similar to observed concentrations in tidal waters); flow-adjusted concentration = concentration adjusted to an average flow year in order to remove effects of variable flow. Trend significance: **, $p<0.01$; *, $p<0.05$; no asterisk, $p \geq 0.05$. Analysis done by the U. S. Geological Survey.

Pollutant Loads Delivered to the Estuary from Sources below the Fall-line

Long-term Perspective

The majority of point sources discharging directly to Potomac tidal waters (e.g. wastewater treatment plants, industrial dischargers) are located in the Washington metropolitan area. The area population grew 13-fold during the 20th century and is now about 5 million. Organic carbon loads from wastewater more than tripled between 1913 and 1944, decreased 91% with better treatment over the next 40 years, and are now at pre-1913 levels. Phosphorus wastewater loads rose over 200-fold, peaked in the 1970s and decreased sharply (98%) before the mid-1980s in response to advanced treatment and the phosphate detergent ban. Loads are now roughly equal to those of the 1920s. Nitrification processes converted ammonia to nitrate but did not removed it. Hence, the estuary experienced an 8-fold rise in nitrogen wastewater loads during the 20th century (Figure 2).

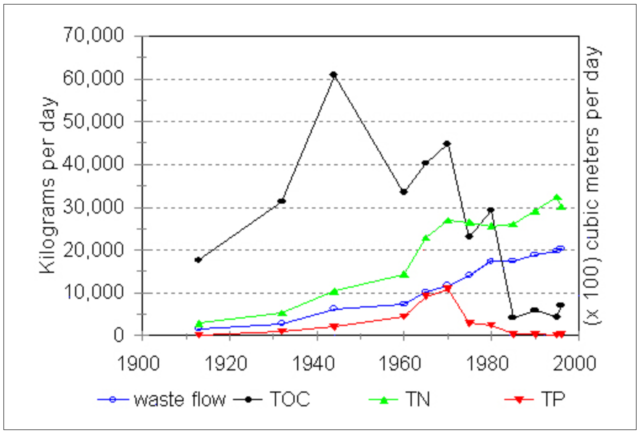

Figure 2. Nutrient loads from wastewater discharged into the upper Potomac estuary below the fall-line. The first Washington, D.C. sewers were built in the 1870s to better channel wastewater into the river. Sewage was untreated until completion of the Blue Plains Wastewater Treatment Plant (WWTP) in the 1930s. Advanced treatment and the construction of additional WWTPs removed much of the organic carbon and phosphorus in wastewater discharged to the river, despite a rapidly growing metropolitan population and a corresponding increase in wastewater flow. Meanwhile, nitrification processes converted ammonium to nitrate but did not removed it. Wastewater treatment upgrades at the Indian Head Naval Warfare Center in 1996 and implementation of a denitrification process at Blue Plains to remove nitrogen in late 1996 reversed the upward nitrogen loadings trend.

CBP Years

Water discharged from wastewater treatment plants (WWTPs) now accounts for about 11% (range: 2% - 39%) of the river flow below Washington, D.C. Nitrogen loads from WWTPs are roughly equal to 50% of fall-line loads due to the higher nitrogen concentrations in the wastewater. The century-long rise in nitrogen wastewater loads was reversed in the mid-1990s by upgrades to industrial dischargers and implementation of denitrification at Blue Plains WWTP. Blue Plains presently contributes 2/3 of the Washington area wastewater flow. Phosphorus and organic carbon loads from WWTPs are presently about 5% and 8% of fall-line loads, respectively, and show no overall trends because their biggest reductions were accomplished before the CBP years. Loads from combined stormwater overflows are probably significant but have not been monitored. Estimated loads of nutrient and sediment entering the estuary below the fall-line in runoff, groundwater, and atmosphere were not assessed.

Ambient Water Quality Status and Trends

The status of most pollution parameters is “fair” or “poor” in Potomac tidewaters relative to other Chesapeake tributaries, although bottom dissolved oxygen is generally “good” in the upper and middle estuary. The 1990s wet years caused an overall increasing trend in estuary flushing rates in the CBP Years (1985 - 1998), and relatively large amounts of nutrients and sediments were transported to Chesapeake Bay. The extent of the nutrient enriched tidal fresh zone was frequently expanded, displacing the oligohaline and mesohaline zones downriver and making the estuary less saline overall. Many of the observed Potomac Estuary water quality trends during the CBP Years can be explained by flow effects of the 1990s wet years.

Phosphorus

The Potomac Estuary water quality response to the drop in phosphorus wastewater loadings has been dramatic. Total phosphorus at monitoring stations in the upper and middle estuary decreased from average monthly concentrations that were at times greater than 0.6 mg/liter in the late 1960s and early 1970s, to concentrations that rarely exceeded 0.15 mg/liter after 1985. Long-term (1965 - 1996) trends in total phosphorus concentrations showed declines of 69% to more than 95%. Trends in total phosphorus and phosphate during the CBP Years were non-significant, presumably because most reduction efforts had been accomplished. Also, management actions that would have indirectly reduced non-point source phosphorus loadings in the CBP Years (e.g. storm ponds, best management practices) were offset by the large, sediment-bound phosphorus loads washed into the estuary during high flow events in the 1990s. Average ambient concentrations of total phosphorus are fairly uniform from the fall-line to the middle of the lower estuary. They are still too high to limit algal growth, except occasionally in the upper estuary during summer and in the middle estuary during winter. Phosphorus concentrations drop off abruptly in the lower estuary, reflecting dilution of Potomac waters by influxes of bottom waters from the Bay mainstem which have lower phosphorus concentrations. These bottom water influxes are greater when freshwater flows are high, and decreasing trends were in fact observed in the lower Potomac during the 1990s wet years. Phosphorus concentrations in the lower estuary are weakly limiting to algal growth during spring, but are rarely limiting during the summer maximum growth period.

Nitrogen

Average concentrations of organic nitrogen, ammonium, and nitrate--the predominant nitrogen forms--quickly increase as tidal fresh waters pass through Washington, D.C., and they remain high between Rosier Bluff in southeast Washington, D.C. and Indian Head, Maryland before finally tapering off in the middle estuary (Figure 3). Nitrogen concentrations are presently never low enough to limit algal growth in the upper and middle estuary, and excess nitrogen is transported downriver. Nitrogen is more completely utilized by the mesohaline phytoplankton populations of the lower estuary, and concentrations eventually drop to levels that control, or limit, phytoplankton growth during summer and fall (<0.07 mg/liter). Long-term increases in nitrogen loads to the Potomac Estuary are thought to be fueling the large summer peak in algal production in the lower estuary and, in the absence of significant grazing pressure by large-bodied consumers (see below), the subsequent algal decomposition is expanding and strengthening bottom water hypoxia and anoxia. Long-term trends (1965 - 1996) show total nitrogen concentrations have increased as much as 20%-40% in the upper Potomac Estuary and 73% in the lower estuary, reflecting steadily rising loads to the upper estuary and increasing transport of nitrogen to the lower estuary. Trends during the shorter-term CBP Years (1985 - 1998) countered the long-term trends: total nitrogen (TN) and dissolved inorganic nitrogen (DIN) trends showed declines as much as 33% and 53%, respectively, at stations in the upper and middle Potomac estuary, and no change at stations in the lower estuary. There are two probable causes of these opposing trends. First, nitrogen concentrations in fall-line waters are significantly lower than those in tidewaters, and the greater quantities of fall-line waters that entered the estuary during the 1990s diluted tidewater concentrations. Second, the tidewater TN and DIN declines may reflect the decreases in Washington, D.C. area point source nitrogen loadings that occurred after 1995. These point source declines should hold tidewater concentrations to lower levels when the dilution effect of fall-line freshwater flows diminishes in average or low flow years.

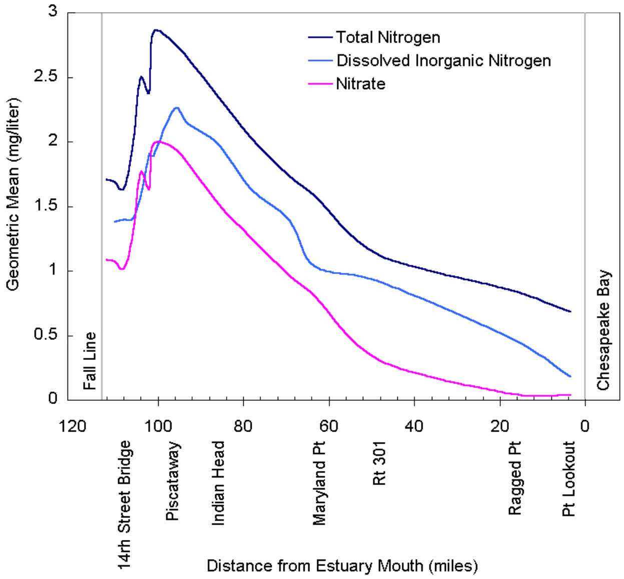

Figure 3. Long-term average concentrations of total nitrogen, dissolved inorganic nitrogen, and nitrate for 1990 - 1996 in the upper and middle Potomac Estuary. River landmarks: D.C. = District of Columbia; Pisc = Piscataway Creek; IH = Indian Head; MD = Maryland Point; Mor = Morgantown; Rag = Ragged Point; PtL = Point Lookout.

Total Organic Carbon

Long-term (1965 - 1996) trends in ambient concentrations of total organic carbon (TOC) fell between 61% (upper estuary) and 12% (lower estuary) to ~6 mg/liter as a result of wastewater treatments between 1940 and 1980 (Figure 2). Ambient TOC concentrations fluctuated sharply between 1976 and 1983, occasionally reaching levels as high as ~37 mg/liter. Massive summer die-offs of the Asiatic clam (*Corbicula fluminea*) are the likely cause of these fluctuations. The upper estuary population of this introduced species underwent extreme cycles in abundance in the mid-1970s and the early 1980s before stabilizing. Total organic carbon concentrations were stable at ~4 mg/liter during the CBP Years and fairly uniform distributed throughout the estuary.

Dissolved Oxygen

Long-term 1965 - 1996 trends for bottom dissolved oxygen show improvements as great as 25% in the upper estuary, despite a return to higher chlorophyll levels at the end of this time period (see below). Dissolved oxygen levels between Washington D.C. and Maryland Point rarely fell below the 5 mg/liter minimum requirement for a healthy habitat (1993 Chesapeake Bay Dissolved Oxygen Goals for Restoration of Living Resource Habitat) after 1980. This improvement can be credited in part to the reductions in phosphorus and organic carbon loads which lowered chlorophyll levels and overall biological oxygen demand (BOD) in the upper and middle estuary. Nutrient load reductions have not restored acceptable dissolved oxygen levels in the lower estuary. In this much larger, deeper segment of the Potomac Estuary, salinity and temperature stratification normally isolate bottom waters in summer and facilitate development of an anoxic/hypoxic zone. Bottom dissolved oxygen worsened between 1965 and 1985, but showed no significant trend during CBP Years.

Water Clarity and Suspended Solids

Water clarity is generally "fair" to "poor" throughout most of the Potomac estuary relative to other Chesapeake tributaries. Potomac tidewaters are naturally clouded by strong tidal mixing in the middle estuary, where salinities transition from fresh to brackish, and a turbidity maximum is expected there. However, water clarity is not much better above or below this maximum due to high concentrations of total suspended solids (sediments, detritus, and phytoplankton) in the water (Figure 4). The annual average secchi depth drops quickly from greater than 1 meter (0.1 - 3.6 meters range) to about 0.7 meter (0.2 - 1.8 meters range) as tidal fresh waters pass the short distance through Washington, D.C. Secchi depth averages (1984-1998) then vary between 0.4 and 0.7 meters the entire length of the upper and middle estuary segments before finally increasing to 1 - 2 meters in the lower estuary.

Water clarity in the upper estuary is presently so poor that it limits phytoplankton growth almost all the time (phosphorus was briefly limiting during the summers of 1991, 1992 and 1998). It also frequently fails CBP tidal fresh habitat criteria for submersed aquatic vegetation (>0.7 meter) between March and September. Water clarity attains the CBP oligohaline habitat criteria for submersed aquatic vegetation (>0.7 meter) about half the time in the middle estuary. However, it almost always limits algal growth. Water clarity in the lower estuary attains the mesohaline submersed aquatic vegetation criteria (>1.0 meter) most of the time and light levels rarely limit algal growth. The potential consequences of high suspended solids concentrations to animals, whether organic or inorganic, have not been assessed. They include deleterious effects on filter-feeding animals, a smothering of benthic organisms either directly with sediments or indirectly with increases in phytoplankton, and disruptions of light-dependent animal behaviors.

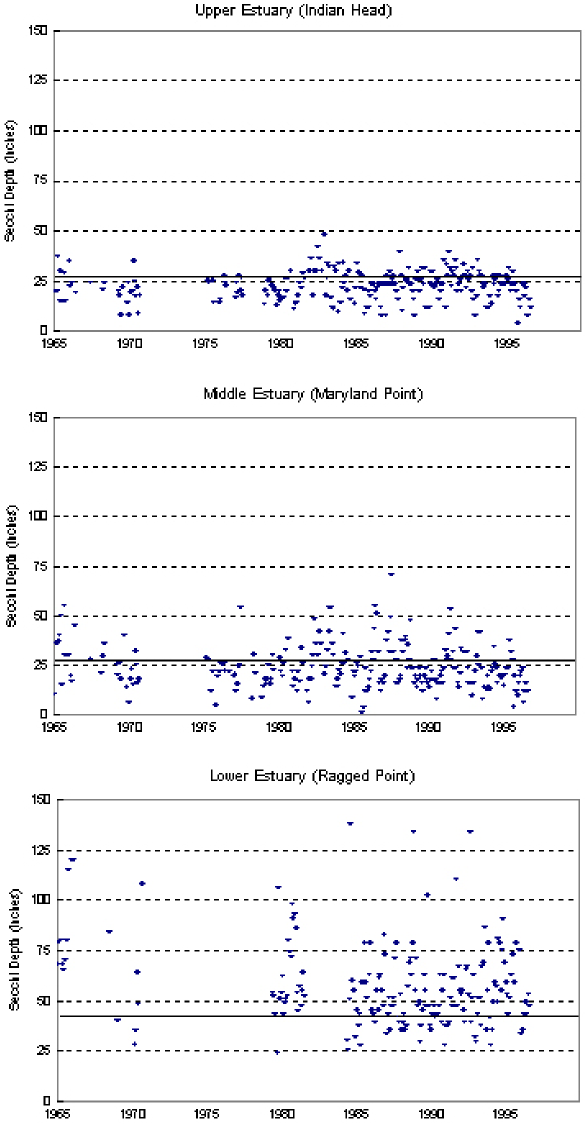

Figure 4. Secchi depth time series for the Indian Head station in the upper estuary, Maryland Point station in the middle estuary and Ragged Point station in the lower estuary, for 1965 - 1996. Solid lines are the submersed aquatic plant habitat criteria for secchi depth: 0.7m for the upper and middle estuary salinities, 1.0 m for the lower estuary salinity. Segment trends (all station data pooled by segment) during the CBP Years (1985 - 1998) were -23.9% ($p<0.01$) in the upper estuary, -20.9% ($p=0.013$) in the middle estuary and -25.3% ($p<0.01$) in the lower estuary.

Average sediment concentrations, and presumably the clarity, of fresh waters entering the estuary at the fall-line improved during the CBP Years (Figure 1) yet ambient concentrations of total suspended solids (TSS) in the upper estuary did not decline and water clarity did not increase. The lack of improving ambient trends was likely due to the observed increase in the phytoplankton component of TSS, and in particular the increase in bluegreen algae. Bluegreen algae are a taxonomic group adept at growing in turbid environments, and they were probably able to respond quickest to the declining sediment concentrations and improving water clarity of the incoming waters. This hypothesis cannot be explored because data on the organic and inorganic fractions of TSS in tidewaters are not available. Long-term (1965 - 1996) station trends in water clarity declined 10% in the middle estuary and up to 30% in the lower estuary. Declines were steeper during the CBP Years (Figure 4), apparently because of increasing trends in TSS and/or bluegreen algae biomass in those reaches of the estuary.

Biological Responses

Biological responses to changing nutrient loads and ambient concentrations are first detected in the microbial realm of bacteria and algae, and then in the submersed aquatic vegetation, benthic macroinvertebrates and zooplankton. All these groups have been studied in the Potomac Estuary during the 20th century and the latter four have been monitored intermittently since the 1960s.

Phytoplankton

Phytoplankton, the base of the aquatic food web, showed enormous community responses to the 20th century eutrophication of the Potomac Estuary. Extensive blooms of freshwater bluegreen algae species proliferated during the summer months of the 1960s, 1970s and early 1980s in a 60 kilometer expanse of the upper and middle Potomac Estuary, between Mt. Vernon and Maryland Pt. The blooms were often dominated by the colonial algae, *Microcystis aeruginosa,* a species of no nutritional value to most large-bodied grazers. Chlorophyll *a*, a quantitative indicator of phytoplankton biomass, frequently exceeded 100 micrograms per liter and phytoplankton were a major component of the suspended solids degrading water clarity. These undesirable characteristics of the phytoplankton community were responses to the high nutrient loads as well as favorable meteorological and flow conditions. Freshwater algae biomass generated in the upper and middle estuary was transported downriver, unconsumed, to die and decompose in the steep salinity gradient usually located between Maryland Pt. and the Route 301 Bridge. In the lower estuary, dinoflagellate algae species dominated in summer, and frequently formed "mahogany tides" or blooms.

Average surface chlorophyll *a* concentrations declined as much as 50% at middle estuary monitoring stations after loadings of the nutrient, phosphorus, were sharply reduced in the mid-1970s. Summer blooms continued to occur in the upper estuary, probably because phosphorus that had accumulated in bottom sediments was still being released to the water. The intensity and downriver extent of upper estuary summer blooms decreased after 1985 and chlorophyll *a* now rarely exceeds 100 micrograms per liter (Figure 5), suggesting that sediment phosphorus is becoming depleted. The upper and middle estuary zones are still extremely enriched, however. Bluegreen algae still dominate the summer populations, and phytoplankton are primarily limited by light and residence time rather than nutrients. Bluegreen algal densities and chlorophyll *a* rose during the 1990s wet years, possibly reflecting the effect of an enlarged freshwater zone and favorable summer weather conditions.

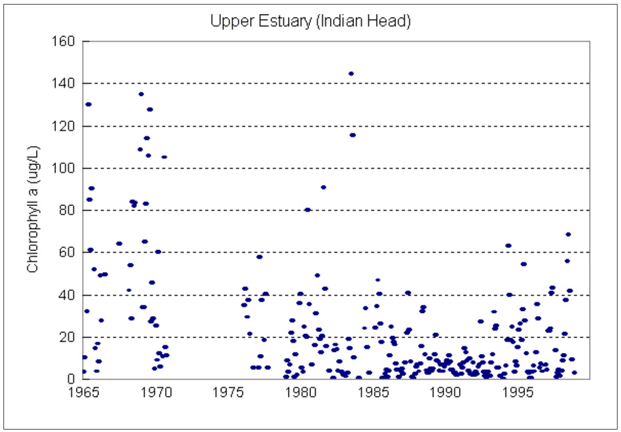

Figure 5. Surface chlorophyll *a* concentrations at the Indian Head station (TF2.3) in the upper Potomac Estuary, 1965 - 1998. Data from multiple sources.

In the lower estuary, chlorophyll concentrations dropped after the 1970s phosphorus reductions but then showed no long-term (mid-1970s - 1996) trends. Chlorophyll concentrations increased slightly during 1990s wet years, and small, filamentous, salt-tolerant bluegreen algae have recently become dominant over estuarine diatoms and dinoflagellates in summer, climbing as high as 68% of the total phytoplankton biomass during August 1998. The shift in species dominance to bluegreen algae in mesohaline waters is unusual and could be related to a number of factors, including degrading water clarity trends, transport of higher nitrogen loads to the lower estuary in the 1990s wet years, or shifting ratios of dissolved inorganic nitrogen and phosphate. Nitrogen is more completely utilized by the mesohaline phytoplankton in the better light environment of the lower estuary, hence summer and fall nitrogen concentrations can become limiting but only after a large algal biomass has built up. Phosphorus concentrations weakly limit algal growth during spring and silicon can limit spring diatom growth in low flow years. Nitrogen reductions in the upper estuary are expected to improve poor dissolved oxygen levels in bottom waters of the lower estuary by directly limiting the spring diatom bloom and indirectly limiting the subsequent algal production and decomposition in summer.

Submersed aquatic vegetation

Flourishing beds of underwater grass, or submersed aquatic vegetation (SAV), once lined the entire Potomac Estuary shoreline and supported abundant fish, invertebrate and waterbird populations. In the 1930s, disease decimated the eelgrass (*Zostera marina*) beds in the lower Potomac Estuary while turbidity (dredging, severe storms) and the exotic SAV species water chestnut (*Trapa natans*) greatly diminished native SAV beds in the upper estuary. During the 1960s, worsening turbidity (algal blooms), another exotic SAV species Eurasian watermilfoil (*Myriophyllum spicatus*), and the cutting and chemical treatment of watermilfoil eventually eliminated all SAV except for narrow bands along the middle estuary shoreline and isolated patches elsewhere. Native SAV returned to the upper estuary only after several years of improved water clarity combined with below-average wind speed and above-average sunlight in 1983. This sudden return was accompanied by the eruption of a third exotic species, *Hydrilla verticillata*. Total SAV coverage quadrupled and distribution spread downriver after 1983 (Figure 6), however the SAV population is not stable. The region of greatest SAV coverage shifted rapidly downriver during the 1990s wet period, and coverage has varied substantially in the past 13 years (Figure 6). Total coverage of the SAV beds in the estuary today is only about 9% of their probable coverage in the early 20th century, and the full habitat and food value of the native species assemblage is still missing. Potomac SAV beds reached 57 % of the CBP Tier 1 Goal and 16% of the CBP Tier 2 Goal in 1998.

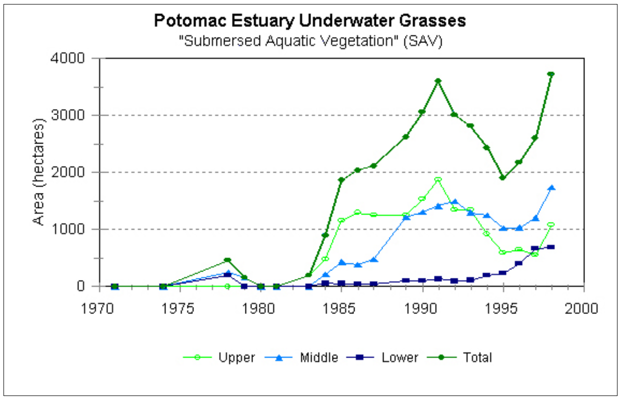

Figure 6. Coverage of submersed aquatic vegetation (SAV) in the upper, middle and lower Potomac Estuary (mainstem only). The upper zone is tidal fresh; the middle estuary is generally oligohaline; and the lower estuary is generally mesohaline. Data were obtained from USGS surveys and from the CBP SAV monitoring program, an aerial survey conducted in summer by the Virginia Institute of Marine Sciences.

In the Potomac Estuary, attainment or non-attainment of the SAV habitat criteria established by the CBP has *generally* corresponded to year-to-year expansion or contraction of SAV coverage, but does not explain all of the changes that have occurred in SAV coverage. Seasonal weather and flow patterns also are important.

Zooplankton

The microbial loop community which includes *bacterio*plankton and *micro*zooplankton (protozoans and rotifers) is thriving in the Potomac Estuary. Concentrations of dissolved organic material largely generated by phytoplankton are presently able to support unprecedented high numbers of bacterioplankton (30-50 million cells per milliliter). High levels of phytoplankton and bacteria in turn support abundant populations of ciliate protozoans and rotifers. Potomac rotifer numbers were among the highest in the Chesapeake system during the CBP Years. Analysis suggests these high abundances may reflect both the very abundant food sources and insufficient predation pressure by higher level consumers such as the copepod *Acartia tonsa*. This clearly demonstrates the continued eutrophic state of the Potomac Estuary.

*Meso*zooplankton abundances in the Potomac Estuary were variable, but usually low, before and during the CBP Years. Mesozooplankton (copepods, cladocera, invertebrate larvae) are an important link in food web pathways leading to fish. Upper and middle estuary abundances were often insufficient for larval anadromous fish in spring, and summer abundances were moderate to low when compared to other

Chesapeake tidal fresh and oligohaline areas. The work of several investigators suggests production rates of important mesozooplankton species are below their full potential in these areas. For example, the estimated productivity of *Eurytemora affinis*, a dominant copepod, during a 1977 study was lower than measured productivity under favorable laboratory conditions. Mesozooplankton are presently not limited by food quantity, however food quality in the upper and middle estuary - and particularly the high proportion of bluegreen algae in the summer phytoplankton - may be one cause of their lower rate of production. Predation pressure from summer planktivorous fish also appears to control mesozooplankton populations in the upper estuary, i.e. mesozooplankton were abundant when planktivores were sparse, and vice versa (Figure 7). In the lower estuary, seasonal abundances were low compared to abundances in other Chesapeake mesohaline areas, and may be controlled by several factors including high predation pressure by jellyfish and fish and poor underwater visibility. The number of mesozooplankton species (species richness) has remained fairly constant in tidal fresh and mesohaline waters since the 1970s indicating no improvement.

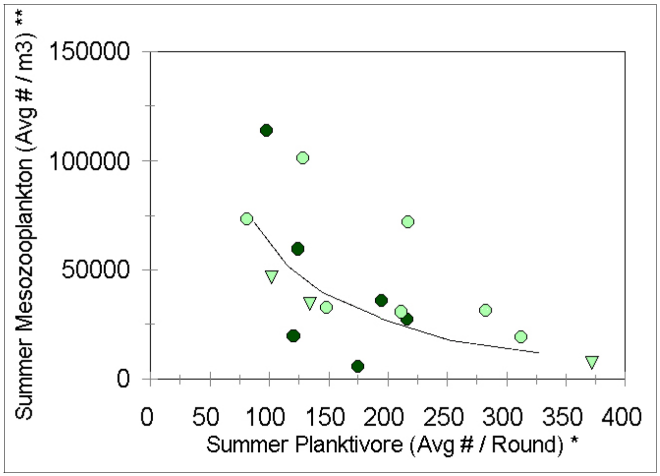

Figure 7. Regression between summer abundances of mesozooplankton and obligate finfish planktivores (i.e. fish that eat zooplankton their entire lives) at the Indian Head, tidal fresh monitoring station in the Potomac Estuary mainstem ($p<0.01$, $r^2=0.71$). Similar relationships were also found upriver in Gunston Cove and the Potomac mainstem adjacent to Gunston Cove. Maryland Summer Seine Survey fish data, historical zooplankton data (1973, 1981), and Chesapeake Bay Program Zooplankton Monitoring Program data (1984 - 1998). Light triangle: SAV absent or in low abundance; light circle: SAV moderately abundant; dark circle: SAV abundant. The presence of SAV in shallow waters may be associated with shifts in the predator-prey data towards one end of the regression curve or the other. SAV is know to significantly affect mesozooplankton and planktivorous minnow abundances in those waters.

However, it has increased 3- to 4-fold in the oligohaline reach of the Potomac, suggesting this middle reach of the estuary is responding more quickly than the others to management actions.

The comb jellyfish (ctenophores) and true jellyfish (cnidarians) are predators on mesozooplankton and fish larvae in mesohaline waters. Ctenophore densities increased in the lower estuary during the CBP Years and their predation rates on mesozooplankton are potentially large. Ctenophores may be increasing because a) lower salinities in the past decade separate them more from their cnidarian predators, and/or b) increasing turbidity (i.e. higher TSS, lower secchi depth) give them a competitive edge against visual predators such as finfish.

Benthos

Benthic invertebrates dwelling in “soft-bottom” areas, or sediments (muds, clays, sands), are another important link in the food web pathways leading to fish. A diverse soft-bottom benthic community inhabited the Potomac Estuary in the first half of the 20th century. *Rangia cuneata* (brackish-water clam) invaded the middle and lower Potomac estuary mid-century, and *Corbicula fluminea* (Asiatic clam) invaded the upper Potomac Estuary in the late 1970s. Both species climbed to very high densities and briefly dominated their benthic assemblages before declining. The benthos of the upper Potomac estuary were stressed by poor dissolved oxygen during the 1960s and 1970s but recovered as oxygen improved, and the present community has some of the highest measures of species richness, total abundance and biomass in the Chesapeake system. Closer examination suggests the upper estuary population is not completely restored since it is dominated by tubifex worms and other pollution-tolerant species. In the middle estuary, an area naturally stressed by salinity fluctuations, species richness is low but has increased during the CBP Years. The Benthic Index of Biological Integrity (BIBI), a multivariate scoring protocol for benthic macroinvertebrate communities, indicates this area occasionally meets the CBP restoration goals. In contrast to the upper and middle estuary, the benthos community in the lower Potomac estuary is the worst in the tidal Chesapeake system, along with the deep trench in the Bay mainstem, and consistently fails the BIBI. This dichotomy is primarily due to the different summer oxygen levels.

The food value of the soft-bottom benthos to higher trophic levels was not assessed, and it is unclear if the community provides sufficient food for benthivore fish predators and diving ducks. Historic benthos levels have not been recovered because submersed aquatic vegetation beds, a habitat inwhich benthos are known to concentrate, are still at only 9% of their historical levels.

Fish and Shellfish

Improvements to-date in habitat and food conditions have not directly stimulated long-lasting increases or complete recoveries in Potomac Estuary commercial fisheries, including oysters. Populations of other large-bodied, long-lived consumers are similarly unchanged, and the Potomac Estuary food web is still dominated by microbial pathways. Aggressive state and federal management has helped striped bass recover from overharvesting in the 1980s. The unstable recovery of submersed aquatic vegetation in the upper and middle estuary has encouraged some fish groups (e.g. minnows, large mouth bass) to increase.

Conclusions and Recommendations

Will the current nutrient reduction policies successfully return the Potomac water quality to desirable and habitable levels? Management actions to control organic carbon and phosphorus loadings, especially those from point sources, significantly reduced ambient concentrations of these parameters in the Potomac Estuary before the start of the Chesapeake Bay Program. These pre-1985 reductions were largely responsible for improving dissolved oxygen to habitable levels (>5 milligrams per liter) in the upper and middle estuary. Actions designed to further reduce phosphorus loadings during the CBP Years have not significantly changed ambient concentrations in the water column. Phosphorous concentrations in the upper and middle estuary still have not reached the desired, low levels that limit phytoplankton growth. However, declines in the extent and intensity of summer bluegreen algae blooms under favorable weather conditions suggest that the release of phosphorus stored in the sediments may be diminishing as the accumulation rate slows.

Recent management actions to reduce point and non-point sources of nitrogen are apparently reversing the century-long climb in nitrogen loads. The resulting decreases in ambient nitrogen concentrations are expected to strengthen nutrient-limitation as the primary factor controlling summer phytoplankton productivity in the lower estuary, and will reduce the amount of nitrogen exported to Chesapeake Bay. The reductions are also expected to lower chlorophyll levels and improve dissolved oxygen in the lower estuary, thereby alleviating the anoxic/hypoxic stress on mesohaline biological communities to some degree. Dissolved inorganic nitrogen concentrations in the upper and middle estuary are presently always above the 0.07 milligram N per liter limitation threshold for phytoplankton growth.

Existing nutrient load reduction strategies could possibly attain the desired, algal-limiting nutrient concentrations if management action is also taken to reduce turbidity. Poor water clarity presently limits algal growth and stresses submersed aquatic vegetation in the upper and middle estuary. As long as light environments remain poor in these areas, further nutrient load reductions will only minimally improve habitat conditions. Degrading trends in the lower estuary suggest the same association of poor water clarity, high nutrient levels and summer blue-green algal blooms is developing in this segment as well. Nutrient reduction strategies may now need to be augmented by strategies to increase light penetration in order to restore healthy phytoplankton and submersed aquatic vegetation communities. Under higher light levels, dissolved inorganic nutrients are more rapidly utilized and converted to particulate organic matter, namely phytoplankton biomass, resulting in faster nutrient turnover and possibly lower concentrations of dissolved nutrients. While higher phytoplankton biomass is not wanted, better light environments and lower nutrient concentrations should allow more desirable algal species to grow. This improved food base should encourage consumption (grazing) by zooplankton and benthos. Similarly, higher light levels should also support more stable, robust growth of submersed aquatic vegetation beds and result in higher abundances of benthic and zooplankton grazers associated with the beds.

Will current nutrient reductions sufficiently improve food and habitat conditions so that the impacts of other stressors are overcome and a balanced, productive ecosystem with abundant fish and wildlife populations is restored? Nutrient reductions to-date have not been sufficient to overcome the other, often mutually-reenforcing anthropogenic impacts to the estuary. In view of the estuary's present status, fully implemented nutrient reduction strategies should also not be expected to do so. This conclusion was expected, given the number and magnitude of anthropogenic impacts that have changed the estuary in addition to nutrient enrichment. Landscape changes after European settlement increased the variability of freshwater baseflows into the estuary by ~40%. Heavier sedimentation filled in many tributaries. Enormous (>98%) losses in many large-bodied, long-lived consumers of the food web, including American shad, river herring and sturgeon, profoundly changed food web dynamics in the 20th century. Major declines in two key "living" habitats (oysters and submersed aquatic vegetation) and blockages to migratory fish have substantially limited the physical habitats available. Exotic species were introduced and are now an integral part of the ecosystem. Bioaccumulation of toxic chemicals has become a persistent problem in the upper and middle estuary and in the Anacostia tributary.

Thus, in order to successfully restore a balanced, productive system with abundant living resources, management strategies for the Potomac Estuary need to become both more holistic and more region specific. For example, halting the degrading trends in the lower estuary may require reducing upriver nitrogen loadings *and* restoring oyster populations (for the purpose of filtering sediments and algae from the water). Actual restoration of the lower estuary may require additional management actions. Furthering the gains made to-date in the upper and middle estuary may require reducing *in*organic sediment loadings above and below the fall-line for the purpose of restoring the ecologically important submersed aquatic vegetation beds and reducing bluegreen algae dominance in the phytoplankton community.

Additional conclusions in this report that confirm or support the results of other Chesapeake Bay Program analyses include:

- Variability is an expected and natural feature of estuaries, and annual variability in freshwater flows can temporarily negate and even offset nutrient reduction efforts.

- Downward nitrogen trends observed in some western Chesapeake tributaries during the 1985 - 1998 period ("CBP Years") may be partly the result of greater dilution by relatively cleaner upstream waters during 1990s high flow years.

- Reductions in point and non-point source loadings of phosphorus may take years and even decades to be fully expressed as reductions in ambient phosphorus and chlorophyll concentrations in the upper and middle estuary.

- Biological populations in the middle of the open water food web currently do not appear to be closely linked to phytoplankton, the base of that food web.

- Populations higher in the food web take more time to recover because of their longer life cycles, and their restoration may require more effort than simply improving habitat conditions (e.g. fish stocking, managed harvests, physical habitat restoration).

- Living resources, especially submersed aquatic vegetation and oysters, may be crucial partners in successfully attaining good water quality and food conditions.

Several issues were raised by this project that can best be answered with further research or data analysis efforts, in order to direct management actions in more effective ways:

- Further investigate the downward trends in ambient total nitrogen concentration and shifts in the proportion of nitrate, to determine how much can be attributed to Biological Nitrogen Removal (BNR) at Blue Plains Treatment Plant.

- Explore the causes of the decreasing water clarity trends in all segments of the estuary.

- Explore the reasons why bluegreen algae have recently increased throughout the estuary, and examine the role of phytoplankton in light attenuation in the upper estuary.

- Investigate mesozooplankton rates of production to determine a) if growth rates are maximal and abundances are low because of predation pressure, flow or some other natural loss function, or b) if growth rates are in fact below the population's potential due to stressful habitat conditions and/or poor food quality. Determine what factors limit microzooplankton production rates and what factors control their total abundance.

- Determine the oyster population abundances required to reduce ambient sediment and nitrogen concentrations in the lower Potomac estuary by up to 40% of 1985 levels, and explore the potential role of restored oyster beds in destabilizing stratification and inhibiting summer anoxia development in the lower estuary.

Management strategies have emphasized nutrient reduction strategies while recognizing the importance of living resources conservation and restoration in achieving good water quality (e.g. CBP Submersed Aquatic Vegetation Restoration Goal, CBP Ecologically Valuable Species Strategy, CBP Oyster Reef Restoration Goal). To further restore the Potomac Estuary ecosystem to a productive, well-functioning state, jurisdictions need to continue to reduce nitrogen and phosphorus loadings and also:

- Improve water clarity.

- Restore two important "living" habitats, submersed aquatic vegetation beds in the upper estuary and oyster reefs in the lower estuary, and key migratory fish passages.

- Restore and/or protect key finfish top predators and mid-level prey species.