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An Ecological Assessment of the Corsica River Estuary and Watershed
Scientific Advice for Future Water Quality Management

FINAL REPORT
to
MARYLAND DEPARTMENT OF NATURAL RESOURCES

By

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Corsica River Estuary Report
Executive Summary
October, 2009

- During the past 30 years it has become clear that nutrient-induced ***eutrophication (over-fertilization with nitrogen and phosphorus***) of estuarine and coastal marine waters has become a serious environmental problem. In 2000, the National Research Council concluded eutrophication to be the greatest threat faced by coastal and estuarine ecosystems. The intensive use of lands adjacent to coastal areas and the continuing movement of people to coastal watersheds will likely intensify this problem. Other science-based reviews confirm the world-wide nature of eutrophication of estuarine waters and the serious consequences of this process.

- In estuaries undergoing eutrophication, ***a number of changes occur***, including the loss of submerged aquatic vegetation (SAV) with replacement by macroalgae and then by dense phytoplankton communities (often with intense blooms of toxic algae), decreases in water clarity, and development of depleted dissolved oxygen conditions (hypoxia) or zones with no oxygen at all (anoxic or “dead zones”). Shifts, some abrupt, often occur, and these shifts can act to accelerate and intensify eutrophication problems. Finally, impacts of eutrophication on estuarine habitats can cause changes in food web structure with some systems becoming more water column dominated (pelagic) rather than bottom dominated (benthic), the latter being the pre-eutrophication condition.

- In 1998 the State of Maryland developed the ***Clean Water Action Plan (CWAP)*** to identify and restore watersheds and associated estuaries not meeting clean water and natural resource goals. The CWAP involved producing full watershed assessments, prioritizing watersheds for restoration or protection and developing restoration strategies. Watersheds were classified into 4 categories, with Category 1 Watersheds not meeting environmental quality goals and in need of restoration. The Corsica River system was classified as Category 1. Because of the degraded condition of the watershed and estuary, the Corsica was given the highest priority (Category 1 Priority) for restoration.

- The CWAP produced ***Watershed Restoration Action Strategies (WRAS),*** which were developed by the MD-DNR and the MD-MDE for 25 Maryland watersheds, the Corsica among them. The Corsica WRAS was initiated in 2003 and in 2005, state agencies were directed to collaborate and select a watershed with a strong watershed plan (WRAS) where aggressive implementation would likely result in improved water quality and habitat conditions. A WRAS plan was initiated in the Corsica watershed. The ultimate goal is to have the Corsica removed from the State’s list of 303(d) impaired waterways.

- The Corsica River estuary is currently listed on the ***Maryland 303(d) list*** of impaired waterways for the following issues, all of which remain in effect at this time and include:
    - Excessive sediments (1996)
    - Over-enrichment with nutrients (1996)
    - PCBs (2002)
    - Fecal coliforms (1996)
    - Impacts to biological communities (2002 and 2004)

  The WRAS developed for the Corsica River watershed identified ***13 actions*** which, if effectively implemented, would likely restore many aspects of Corsica River water quality, habitats and living resources.

- The major accomplishment thus far is the nutrient reduction achieved with the Centerville waste water treatment plant upgrade to ***Enhanced Nutrient Removal (ENR) status*** coupled with spray irrigation of treated waste water onto agricultural fields. Less progress has been achieved with other Best Management Practices (BMPs).

- The ***major purpose of this report*** is to synthesize the data collected in the Corsica River basin and estuary during the past 5 years and use these data to evaluate the following:
    - Determine the sources of N and P to this estuary
    - Characterize water quality and habitat conditions in the estuary
    - Develop relationships between N and P inputs and responses of the Corsica River ecosystem
    - Estimate the possible N and P load reductions associated with implementation of all BMPs
    - Forecast the likely responses of the Corsica River ecosystem to these potential N and P load reductions

- ***The Corsica River watershed*** covers 25298 acres of Queen Anne's County, Maryland and is dominated by agricultural land uses (60%), with forested (27%) and developed land uses (7%) accounting for the rest of the land area. Population in Queen Anne's County was stable until the construction of the first and second spans of the Bay Bridge in 1952 and 1973, respectively. Suburban sprawl has consequently increased in the Corsica River watershed in recent decades, mostly in the vicinity of Centreville. One result of the diffuse distribution of residences in the watershed is that nutrient loads from septic systems are now estimated to be larger than those from the recently upgraded Centreville Sewage treatment plant.

- ***Water quality in the Corsica River*** estuary remains impaired. Water clarity is very poor with most of the bottom of this very shallow estuary receiving no light. Nutrient concentrations remain very high (well above concentrations limiting algal growth). The index of algal abundance used here (chlorophyll-a concentrations in the water) also remains very high and contributes to poor water clarity. Finally, during summer periods there are frequent episodes where dissolved oxygen concentrations are very low, impacting aquatic life. Several fish kills have been observed in recent years. In general, water quality is most severely degraded at the head of the estuary and improves toward the junction with the Chester River.

- ***Nitrogen and phosphorus loads*** to the Corsica are substantial (compared to other estuaries) and are dominated by diffuse sources, mainly from agricultural operations (corn and soybean fields). These diffuse loads must be substantially reduced before Corsica water quality will improve.

Summary of average total nitrogen and total phosphorus loads to the Corsica River estuary from all sources. Data are mainly from 2007. See Appendix for data sources and details concerning estimation procedures[18].

Nutrient Source	Total Nitrogen Load (kg N per month)	Total Phosphorus Load (kg P per month)
Diffuse Sources	8099	1002
Stormwater Runoff	1023	345
Direct Atmospheric Deposition	452	~0
Point Sources	168	17
Septic Leachate	149	~0
Total Load	**9891**	**1364**

- ***Permanent losses of nitrogen*** from the Corsica River estuary include export of N to the Chester River (~43% of inputs), denitrification (loss to N back to the atmosphere as biologically inert N_2 gas; ~34%) and burial of N in bottom sediments of the estuary (18%). The fact that estimates of inputs are very close to estimates of N losses indicates that all major inputs and losses have been adequately estimated.

- ***Algal blooms and nitrogen loads*** are strongly related in the Corsica (as well as in other shallow estuarine ecosystems). In a multi-system statistical analysis, spring N loading and summer chlorophyll-a were found to be highly correlated. These correlations were not linear and indicate the potential for large declines in chlorophyll-a in response to nitrogen load reductions. The Corsica River estuary currently exists near this potential nitrogen load “tipping point”. Results suggest that a 50% reduction in N loading to the estuary would produce a 70% decline in chlorophyll-a.

- ***Corsica River water is very turbid*** and little light reaches the bottom. Currently, only 10% of the estuary bottom has sufficient light to potentially support SAV communities and only about 28% of the bottom receives enough light to support benthic algae. However, if the water column was clearer by reducing chlorophyll-a concentrations, then the entire upper portion of the estuary would have at least

1% of light reaching the bottom and more than half the lower estuary would receive 1% of surface light to the bottom. The important point here is that a relatively small change in water clarity would greatly increase the area of bottom receiving adequate light for growth of beneficial plant communities.

- A strong quantitative link was also between ***phytoplankton chlorophyll-a and hypoxia*** (or low dissolved oxygen conditions). Corsica River data were analyzed to record all occurrences of hypoxia. The most frequent and intense hypoxic events occurred in the upper estuary. Statistical analysis indicated that hypoxia events frequently occurred during days with very warm water temperatures (>28^{o}C), cloudy conditions, and low wind speeds. Hypoxia was recorded during summer in all regions of the Corsica estuary, but was most intensive during June-August in the upper Corsica River estuary at the same location where algal blooms were most intense. Summer chlorophyll-a concentrations were highly correlated with summer hypoxia at all stations in the Corsica River suggesting a strong link between nutrient loading, chlorophyll-a, and hypoxia. Consequently, it is anticipated that reductions in nutrient load will decrease both the duration and frequency of hypoxic events in the Corsica River estuary, especially if summer chlorophyll-a concentrations could be consistently reduced to below 20 mg m^{-3}.

- An assessment was made of possible ***nutrient load reductions*** using various Best Management Practices (BMPs). Nitrogen inputs to the Corsica River were about 129000 kg N/year prior to 2005. After the upgrades to the waste water treatment plant loads were reduced to about 119000 kg N/year. If septic systems were upgraded to remove N, if storm water was treated to also remove N, and if an aggressive cover crop program were instituted, estimates indicate N loads to the estuary could be reduced to about 73000 kg N/year (about a 50% reduction).

- Predictions for ***Corsica River responses to nutrient load reductions*** include the following: we would expect a 50% reduction in nutrient loading to yield a 70% reduction in summer chlorophyll. Such a reduction in chlorophyll-a would also lead to a 75% improvement in water clarity, which, because of the areal distribution of water depth for the Corsica River estuary, would lead to a nearly 95% increase in the area of Corsica river sediments that could support benthic algae and 60% increase in estuarine area that would provide SAV habitat. The same 50% reduction in N load and associated chlorophyll-a decline would also reduce the number of hypoxic hours in the estuary by 80%, essentially eliminating this water quality problem. Current hypoxia levels have certainly restricted important habitats for fish and benthic invertebrate species during the summer and removal of hypoxia would surely benefit the ecosystem.

INTRODUCTION

Nutrient Enrichment: What is it and how long has it been a problem?

During the past 30-40 years, it has become increasingly clear that nutrient-induced eutrophication (over-fertilization with nitrogen and phosphorus) of estuarine and coastal marine waters has become a serious environmental problem[1]. In 2000, the National Research Council[2] concluded eutrophication to be the greatest threat faced by coastal and estuarine ecosystems. That assessment seems as true today as it did almost a decade ago. The intensive use of lands adjacent to coastal areas and the decades-long movement of people to coastal watersheds will likely continue and intensify this problem. Other science-based reviews confirm the world-wide nature of eutrophication of coastal waters and the serious consequences of this process[3, 4].

Typically, in estuaries undergoing eutrophication, a number of changes occur, including the loss of submerged aquatic vegetation (SAV) with replacement by macroalgae and then by dense phytoplankton communities (often with intense blooms of toxic algae), decreases in water clarity, and development of depleted dissolved oxygen conditions (hypoxia) or zones with no oxygen at all (anoxic or "dead zones")[5]. Shifts, some abrupt, in the biogeochemistry and cycling of major nutrients (nitrogen and phosphorus) often occur, and sometimes these shifts can act to accelerate and intensify eutrophication problems. Finally, impacts of eutrophication on estuarine habitats can cause changes in food web structure, as some systems become more water column dominated (pelagic) rather than bottom dominated (benthic), which in these shallow systems appears to be the pre-eutrophication condition.

The Chesapeake Bay has been experiencing the effects of eutrophication for centuries, with the earliest signs (increased organic matter in sediments) appearing about 200 years ago, increased and changing algal communities and decreased water clarity appearing about 100 years ago, and hypoxia in deep waters and loss of SAV occurring about 60 and 50 years ago, respectively[6]. It is likely, because of even closer contact with the land and slow flushing rates, that Bay tributaries and sub-tributaries like the Corsica River, have been exposed to eutrophication processes for as long or for even longer time periods than the mainstem Chesapeake Bay.

Restoration in the Bay and its Tributaries

While there have been restoration projects underway in Chesapeake Bay for many decades (e.g., oyster shell plantings), major remediation efforts began with the inception of the multi-State-USEPA Chesapeake Bay Program in 1984. Several times during the intervening years EPA and the Bay states have committed to major goals for the reduction of nutrient (Nitrogen, N, and Phosphorus, P) and sediment inputs to be achieved using a variety of Best Management Practices (BMPs). These BMPs include a long list of activities such as changes in agricultural practices (e.g., cover crops, no-till field management, nutrient management), planting riparian buffers, storm water management in urban and residential areas, upgrading of sewage treatment plant operations to remove N and P, installation of N-removing septic systems, and others.

It was recently reported that about 4700 restoration projects, both large and small, have been undertaken in the Chesapeake Bay watershed since 1990 at a cost of about $400 million dollars[7]. Unfortunately, only a small fraction (~5%) of these efforts has been evaluated for effectiveness. It is likely that much more could have been learned about restoration effectiveness if more of these sites had been monitored appropriately.

In Chesapeake Bay and tributary rivers, water quality variables, habitats and some living resources have remained about the same during the last 25 years. There have also been a few marked improvements, as well as some serious declines. Restoration processes in both the non-tidal and tidal areas of the Bay are clearly far from completed.

Corsica River Restoration Program

Just over a decade ago (1998) the State of Maryland developed the Clean Water Action Plan (CWAP) to identify and restore watersheds and associated estuaries not meeting clean water and natural resource goals and to protect those currently meeting these goals[8]. The CWAP involved producing full watershed assessments, prioritizing watersheds for restoration or protection and developing restoration strategies. Watersheds were classified into 4 categories, with Category 1 Watersheds not meeting environmental quality goals and in need of restoration. The Corsica River system was classified as Category 1, because of the degraded condition of the watershed and estuary.

The final component in the CWAP was development of Watershed Restoration Action Strategies (WRAS), which were developed by the Maryland Department of Natural Resources and the Maryland Department of the Environment for 25 Maryland watersheds, including the Corsica. The Corsica WRAS was initiated in 2003, and in 2005 the Maryland Governor directed state agencies to collaborate and select a watershed with a strong watershed plan (WRAS) where aggressive implementation would likely result in improved water quality and habitat conditions[9]. The ultimate goal is to have the Corsica removed from the State's list of 303(d) impaired waterways. In 2006 the estimated total cost of this watershed restoration was about $19.5 million dollars invested over a 5-year period.

Specific Issues and Solutions for the Corsica River Watershed

The Corsica River estuary is currently listed on the Maryland 303(d) list of impaired waterways for the following issues (below), all of which remain in effect at this time.

- Excessive sediments (1996)
- Over-enrichment with nutrients (1996)
- PCBs (2002)
- Fecal coliforms (1996)
- Impacts to biological communities (2002 and 2004)

The WRAS developed for the Corsica River watershed identified 13 actions which, if effectively implemented, would likely restore many aspects of Corsica River water quality, habitats and living resources.

What's the Progress to Date?

Recently, the Maryland Department of Natural Resources developed an update of Corsica River restoration program progress. The progress of implementing restoration programs is listed below:

•	Septic system upgrades	27%	(8 of 30 systems; ~809 systems in the basin)
•	Stormwater management	0%	(24 of 300 acres in design phase)
•	Waste water treatment	100%	(Operating at ENR with spray irrigation)
•	Stream miles restored	0%	(0 of 3 miles)
•	Forested buffers	6%	(12 of 200 acres)
•	Oyster restoration	50%	(10 of 20 acres)
•	Wetland restoration	64%	(32 of 50 acres)
•	Horse pasture management	46%	(23 of 50 acres)
•	Conservation Reserve Enhancement Program	60%	(60 of 100 acres)
•	Cover crops	41%	(1621 of 4000 acres)
•	Small grain enhancement	69%	(1371 of 2000 acres)

Purpose of this Report

The primary purposes of this report can be summed up in three parts: ***synthesis, understanding, and forecasting***.

Synthesis: Over the past 5 years, several research and monitoring efforts were conducted in the Corsica River and watershed; some of these efforts continue. For example, high-frequency (every 15 minutes) measurements of temperature, salinity, and dissolved oxygen have been made at 3 sites from 2005 to the present. Three major streams draining into the Corsica have been gauged and stream flow and nutrients have been measured since 2006 and these activities continue. Measurements of key estuarine biogeochemical processes have been made at various times since 2003. A full list of all the valuable monitoring and research programs and reports would be quite long and diverse, but any one of these reports is insufficient to generate a full and useful picture of the status of conditions in the basin and estuary and what efforts might be needed for full restoration. However, a quantitative, synthetic analysis of all the varied research and monitoring programs would permit advanced understanding of the Corsica ecosystem. A simple example involves the amount of nitrogen entering the Corsica River estuary. In this case, a synthesis would include using the gauging station information to estimate diffuse inputs from the watershed, using atmospheric deposition data to estimate the loads from the atmosphere to the surface waters of the estuary, data from the sewage treatment plant to quantify the point sources, septic system data to augment the diffuse source data, and a mathematical model to estimate the exchange of nitrogen between the Corsica and Chester Rivers. One important aspect of synthesis work is that results are at the space and time scales useful for water quality managers.

Understanding: The second feature of this report summarizes the findings of the ***synthesis*** toward understanding the important external drivers and internal linkages in the Corsica ecosystem. The Corsica River is typically very turbid, but is this turbidity caused by suspended sediments, unicellular algae, or some combination of both? One important question for restoration is how much of a reduction in suspended sediments or algae would be needed for enough light to reach the bottom to support growth of SAV. There are several such critical cause-effect linkages evaluated in this report.

Forecasting: This report also considers ***forecasting*** of future water quality and habitat conditions. One goal of this effort is to suggest the likely outcomes of several scenarios, based on our ***understanding*** of the ecosystem. In this case we make estimates of the magnitude of nutrient load reductions possible based on implementation of various BMPs and, using those load reductions, forecast the likely ecosystem responses to load reductions. Finally, based on our experience with the Corsica River Restoration Program we generate some ***guidelines for future restoration projects*** that will assist in site selection and efficient project operations.

DEGRADATION AND RESTORATION OF THE CORSICA RIVER ESTUARY

At the outset of this project, it is important to develop a full and clear conceptualization of how key properties and processes of the Corsica estuary have changed in response to human influence. In effect, we need an integrated hypothesis of how the ecosystem has been degraded and how it would look in a restored state. A simplified conceptual model of the Corsica is provided in Figure 1[10], showing both the current degraded condition and what is expected if the estuary is restored.

In the current degraded condition (right panel of Figure 1), nutrient inputs (both N and P) to the estuary are high and these nutrient loads lead to phytoplankton blooms, turbid water with very little light reaching the bottom, low dissolved oxygen (O_2) conditions (especially during summer), essentially no SAV community, and occasional fish kills. The lack of light reaching the bottom of the estuary precludes growth of benthic diatoms, which act (1) not only as a high quality food source for some organisms, but also (2) stabilize sediments (preventing sediment resuspension) and (3) absorb a large fraction of the N and P released from bottom sediments by bacterial decomposition.

The expectation is that if nutrient and sediment loads from the watershed are substantially decreased, the estuary will respond in a number of ways, including: (1) with lower nutrient loading rates, phytoplankton blooms will be less dense and of a more limited duration; (2) reduced algal blooms, coupled to reductions in sediment inputs, will lead to increased water clarity, allowing benthic diatoms and possibly SAV to flourish in shallow areas (<1 m depth). Both SAV and benthic diatoms will further reduce the amount of sediment resuspension and this will reinforce the trend toward clearer waters; (3) O_2 conditions will return to more normal status (i.e., O_2 being neither very high or very low), and this will favor the development of a robust benthic animal community that

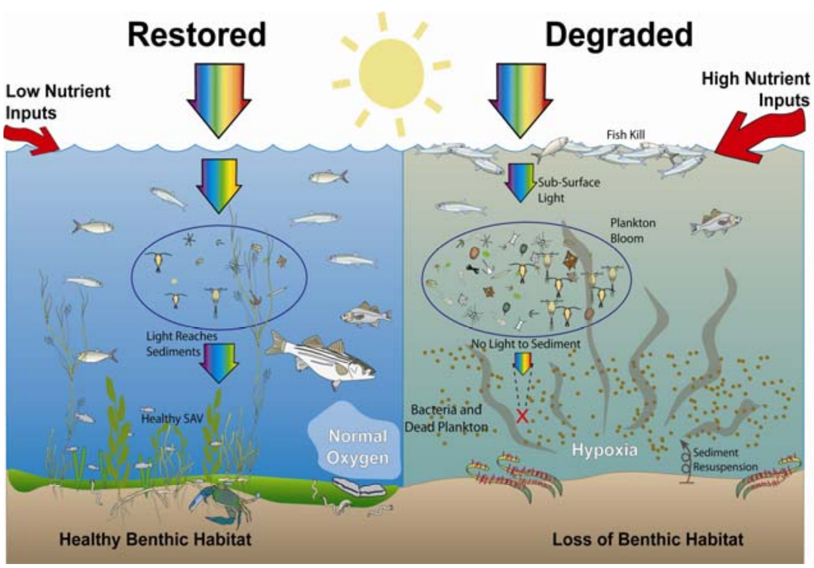

Figure 1: Conceptual diagram of ecological processes occurring in a restored and degraded Corsica River estuary. It is estimated that the nutrient load to the Corsica needs to be reduced by a factor of about 2 to restore the system to a healthy status.

will further stabilize sediments, provide a food source for fish and crabs, and filter additional material from the water.

What this simple diagram does not capture is an idea of how fast or slow these processes leading to either further degradation or restoration will occur. That's a more difficult question and there remains considerable uncertainty about these outcomes. For example, it is quite certain that nutrient loads coming from groundwater sources will be slow to respond (years to decades) to management actions. On the other hand, if nutrient supplies are substantially reduced, evidence from other portions of Chesapeake Bay and other estuaries indicate that algal blooms and hypoxic waters will respond favorably very quickly (months to year). Re-establishment of SAV communities would probably require several years, as with some other components of the benthic community.

In addition to these estimates of recovery times, there is the issue of ecological thresholds, which have recently received a good deal of attention[11]. In simple terms, thresholds are defined where a relatively sudden and large change in some important ecosystem component or process occurs at a specific level of one of its controlling variables. For example, if water clarity improved so that adequate light reached the bottom of the estuary, there might be a sudden change in sediment biogeochemistry leading to much smaller amounts of N and P recycled back to the water column, resulting in smaller summertime algal blooms per unit watershed N and P loads.

CORSICA LAND-WATER CONNECTIONS

The Watershed

The Corsica River watershed covers 25298 acres of Queen Anne's County, Maryland and is dominated by agricultural land uses (60%), with forested (27%) and developed land uses (urban plus suburban areas, 7%) accounting for the rest of the watershed land area (Figure 2)[12]. Agriculture is mostly in the form of crop cultivation, with corn, soybeans and wheat being the principle crops. Tidal marshes form a small portion of land use, but both brackish tidal and palustrine streamside wetlands are present in the watershed. Although population increased rapidly in Maryland following WWII, the population

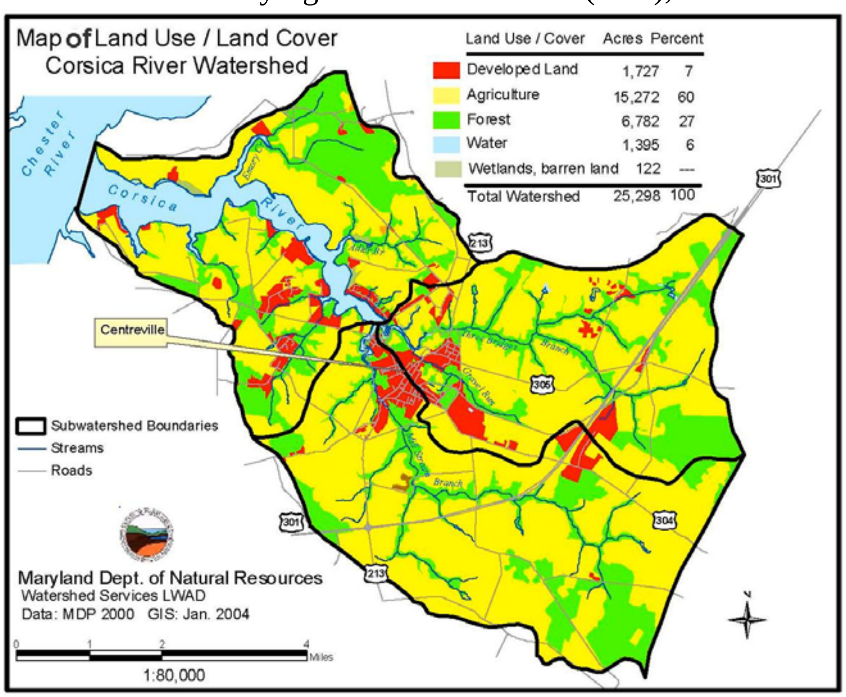

Figure 2: Map of the Corsica River watershed, including categorized land-use types (see color code), sub-basin boundaries (dark solid lines), and major streams entering the Corsica River estuary.

in Queen Anne's County was stable until the construction of the first and second spans of the Bay Bridge in 1952 and 1973, respectively (Figure 3). Suburban sprawl has consequently increased in the Corsica River watershed in recent decades, mostly in the vicinity of Centreville. However, agriculture still remains the dominant land use. One result of the diffuse distribution of residences in the watershed is that nutrient loads from septic systems are now estimated to be larger than those from the recently upgraded Centreville Sewage treatment plant.

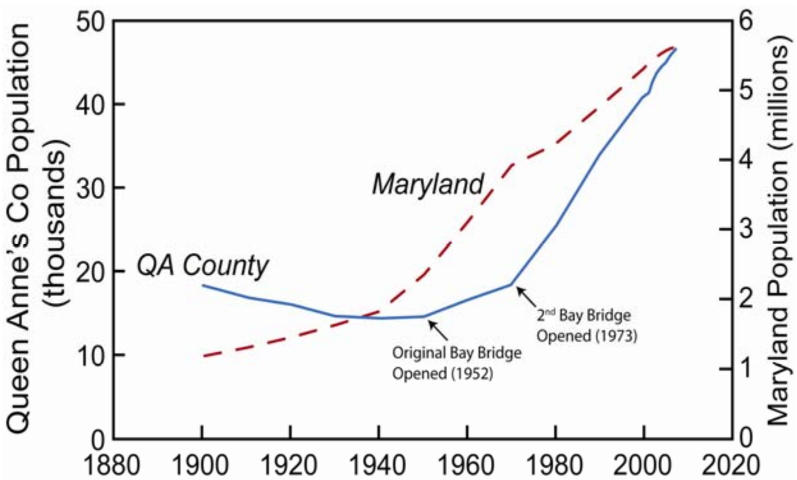

Figure 3: Population change in Maryland and Queen Anne's County.

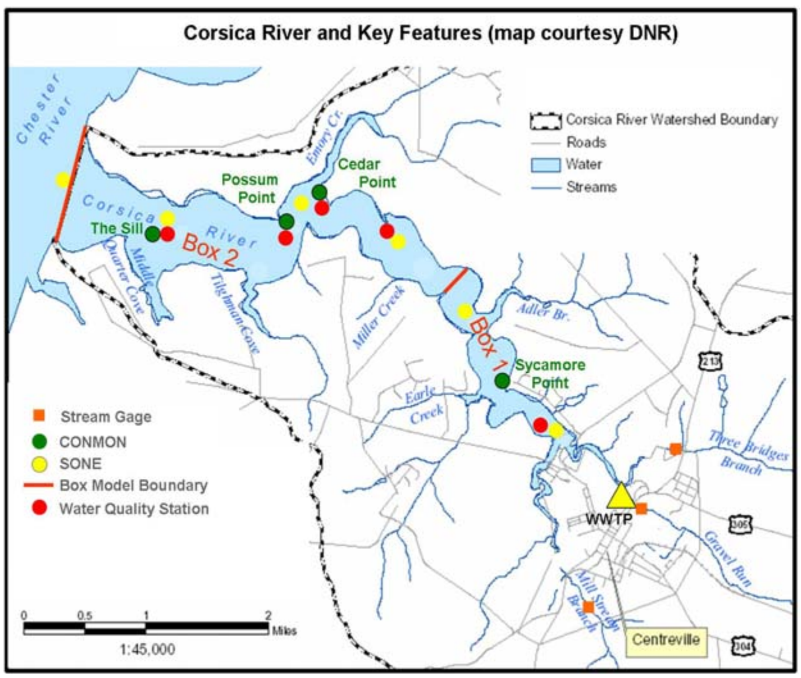

Figure 4: Map of the Corsica River estuary showing locations of water quality monitoring stations (red dots), Steam gages (orange squares), high frequency monitoring sites (CONMON; green circles), sediment oxygen and nutrient exchange (SONE) and denitrification measurement sites (yellow circle) and boundaries used in the box model used to compute nutrient transport (red lines)[21].

Water Quality

Many water quality variables have already been monitored in all regions of the Corsica estuary, both continuously (CONMON: salinity, O_2, chlorophyll-a, water temperature, pH) and monthly (Figure 4)[13,14]. These regions include the headwater region of the estuary (Sycamore Point), the middle region of the estuary (Possum Point), and the most seaward region of the estuary near the connection to the Chester River (The Sill). Nutrients, sediments, and varied organic particles, delivered to the Corsica River estuary from its watershed play a large role in determining the water quality of the estuary, (SAV, dissolved oxygen). Seasonal cycles of chlorophyll-a (an index of algal biomass in the water column) and O_2 (collected by CONMON) at Sycamore Point, Possum Point, and The Sill show similar seasonal patterns, suggesting that water quality drivers are similar in all regions of this system (Figure 5).

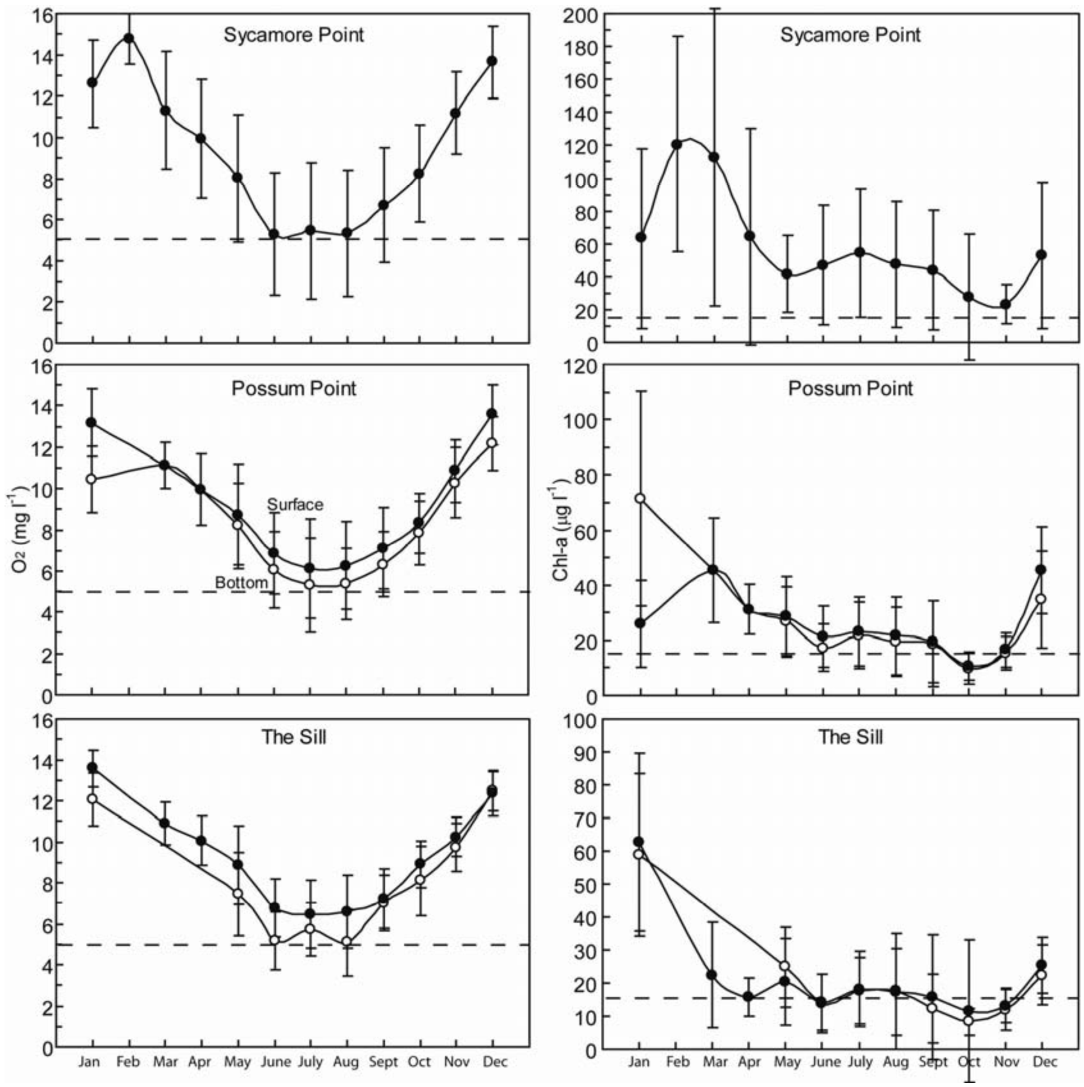

Figure 5: Monthly mean dissolved O_2 and chlorophyll-a (± Standard Deviation) at three stations in the Corsica River estuary. See Figure 2 for these station locations. Data are from the CONMON Program of high frequency water quality monitoring (2005 to 2008). The averages (each dot or circle) are based on approximately 12000 Observations. Note that the lowest dissolved oxygen conditions occur during June-August at all sites while the highest chlorophyll-a concentrations (an index of algal blooming) occur in winter at all sites. Note that chlorophyll-a figures have different scales. Dashed lines represent water quality values associated with little or no O_2 stress (O_2 = 5 mg l^{-1}) and adequate conditions for SAV growth (chlorophyll-a = 15 mg m^{-3}). Filled circles = surface water; open circles = sensors near bottom.

Daily mean dissolved O_2 concentrations are high in winter, spring, and fall, but consistently fall below values associated with O_2 stress on resident fish and invertebrates during the months of June, July, and August, when high temperature reduces the solubility of oxygen in water and increases the rate of respiration in the water column and sediments (Figure 5). Sycamore Point, a station roughly 1 meter in depth, consistently had lower daily mean summer O_2 concentrations than the deeper bottom waters (2.4-3.7 m) of the Sill and Possum Point sites (Figure 5), and this pattern is driven by the severe nighttime hypoxic events that occur in this region.

Chlorophyll-a displayed a January to March peak in all regions of the estuary, but was 2-3 times higher and more variable at Sycamore Point than the other two stations

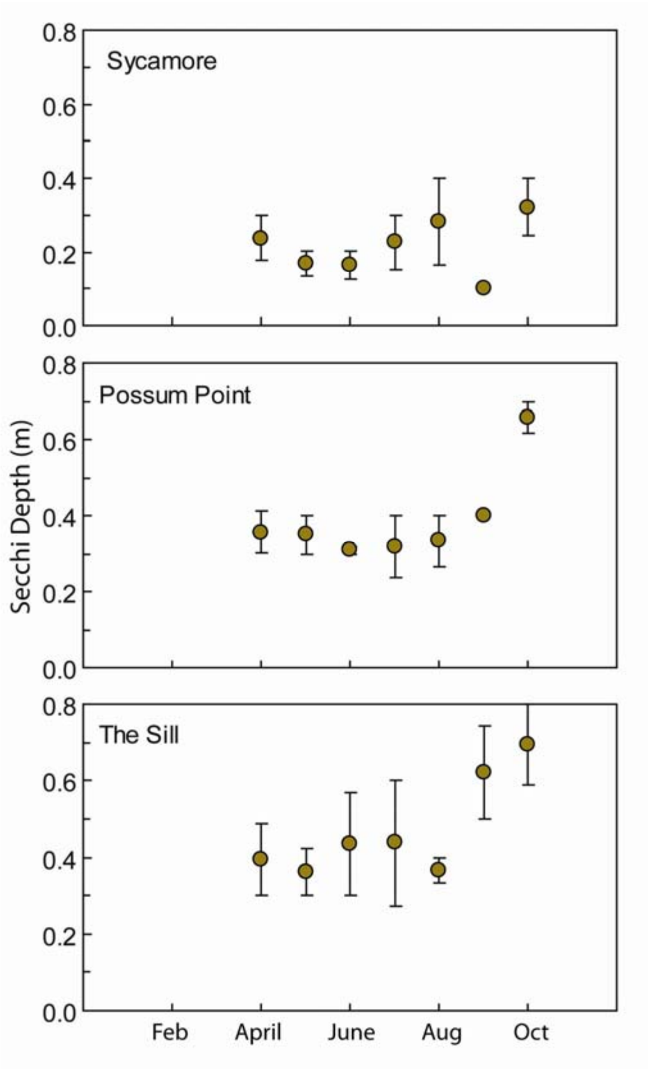

Figure 6: Monthly mean Secchi Depth (± Standard Deviation) at three stations along the axis of the Corsica River estuary. Data are from 2006-2007. In general, water clarity decreases towards the head of the estuary and is better in fall at all sites than during spring and summer. See Figure 2 for station locations.

(Figure 5). Chlorophyll-a values in the Corsica River exceeded those that are adequate for SAV growth during nearly all months in all three Corsica regions (Figure 5).

As a consequence of such high chlorophyll-a values and other sources of turbidity, Secchi Disk depth (an index of light availability in the water column) was low in the Corsica relative to other estuaries, especially during highly productive summer months (Figure 6)[15]. Secchi depth measurements indicate that <28% of the bottom area of the Corsica estuary receives more than 1% of the surface solar radiation (despite extremely shallow depths). Such high light attenuation prevents the growth of SAV and benthic algae on the sediment surface, where SAV require 15% of surface light to survive and benthic algae need 1%. For example, only sediments in the very upper region of the Corsica estuary received 1% of surface light during May and August, suggesting that water clarity must increase greatly to allow for widespread SAV growth (Figure 7). Sycamore Point has very limited Secchi depth from spring - fall, but Secchi depth increases during the autumn months are evident at the Possum Point and Sill sites (Figure 6).

Nutrient concentrations (N and P) in the Corsica estuary[15] exhibited three distinct characteristics: (1) a general pattern of steadily decreasing nutrient concentrations from the upper estuary to the mouth of the estuary (for both dissolved inorganic forms (DIN, DIP) and totals (TN/TP), (2) more seasonal variability in DIN than TN at all stations, and (3) a seasonal peak in DIN in winter-spring and for DIP in June-August (Figure 8). Nutrient concentrations are highest near Sycamore Point because that station is immediately adjacent to streams that deliver ~70% of freshwater (and associated nutrients) from the watershed. DIN peaks in spring when river discharge is highest and declines gradually during the year as it is assimilated by algae and converted to TN. Thus, a seasonally stable TN pool is comprised of mostly inorganic N during spring and by organic (algal) N during the summer and fall months. DIP concentration peaks during summer when spring inputs of P, which are delivered attached to particles and stored temporarily in sediments during spring, are released to the water column from sediments[16]. Reduced O_2 concentrations in summer enhance such sediment-water DIP fluxes. Seasonal ratios of DIN and DIP concentrations in the upper and lower Corsica indicate that DIN is the generally limiting nutrient for phytoplankton growth in the estuary from July to October, but DIP is potentially limiting growth from April to June in the upper estuary, and in April in the lower estuary. These conclusions are based on data indicating that phytoplankton organic matter generally has an N:P *molar* ratio of 16:1. When ambient N:P ratios exceed 16:1 (as in winter and spring), P is the likely limiting nutrient. However, when

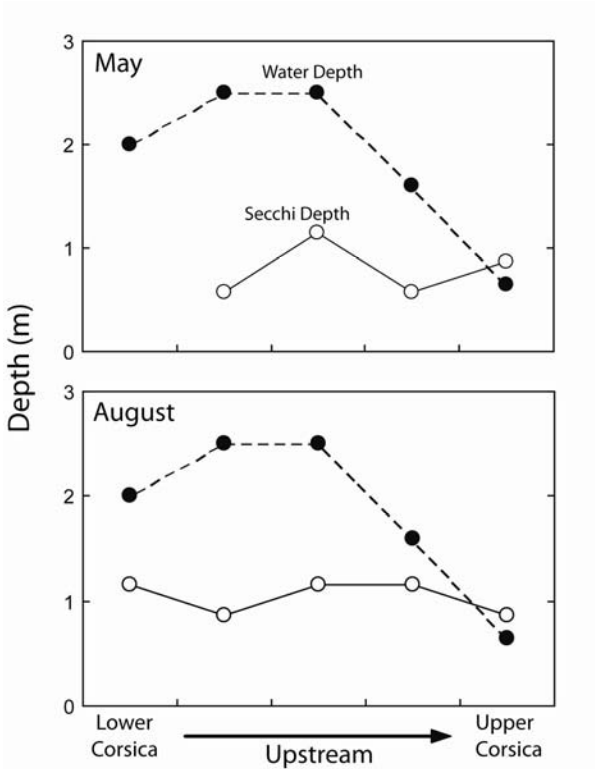

Figure 7: Axial distributions of the mean depth of the Corsica estuary (filled circles) and the depth of 1% light ($Z_{1\%}$) for two months in 2006 (open circles). These data indicate that light only reaches the bottom (mean $Z \leq Z_{1\%}$) in the most upper reaches of the estuary where water depths are very small (< 1m).

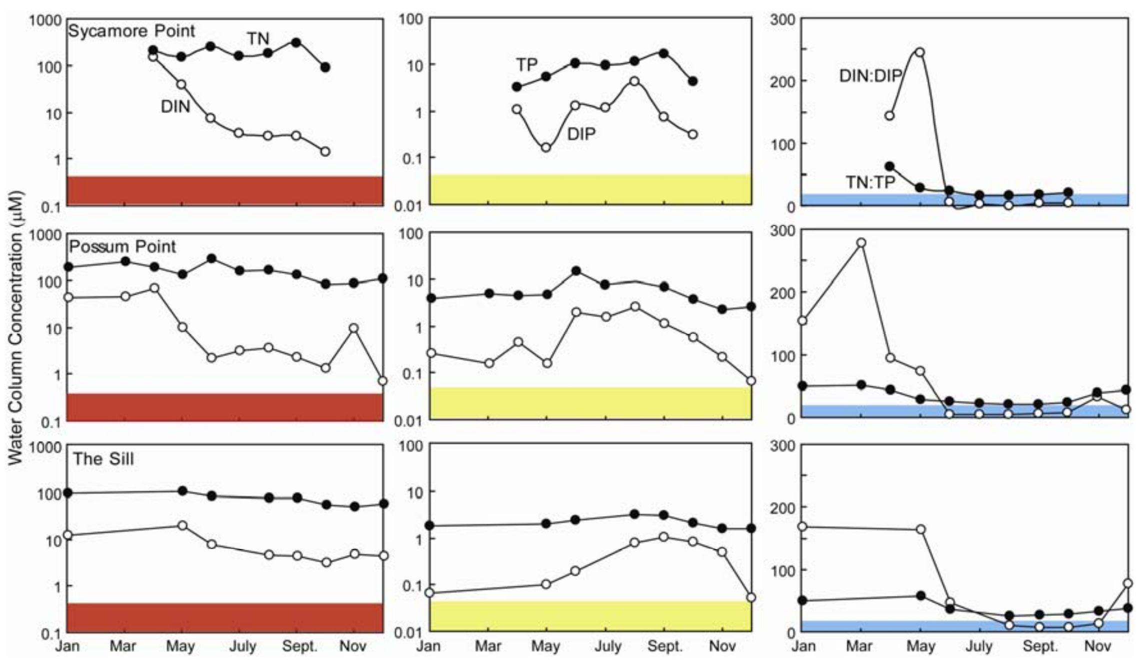

Figure 8: Monthly mean TN and DIN (left panel) and TP and DIP (middle panel) concentrations (note log scale) and DIN:DIP and TN:TP ratios (right panel) in three regions of the Corsica River estuary. Shaded areas (red for N, yellow for P, blue for N:P) indicate the potential for nutrient limitation. Nutrient concentrations are almost always well above limiting concentrations, especially during winter for N and during summer for P. The panel on the right indicates the abundance of N and P relative to the needs of phytoplankton for growth. Data in this figure are from 2007. See Figure 2 for station locations.

N:P ratios fall below 16:1 in summer and fall, N limitation is likely. Because chlorophyll-a concentrations were high in P-limited spring months and also high in N-limited summer months, both N and P should be targeted for load reductions.

NUTRIENT SOURCES

What Sources Were Considered?

In this synthesis of Corsica basin and estuary measurements, five different nutrient sources were evaluated, mainly for the years 2006 and 2007 for which adequate information was available. These nutrient sources (both nitrogen (N) and phosphorus (P)) included diffuse sources, such as runoff from the land (both surface and groundwater)[17], stormwater runoff from the town of Centerville[18], MD, direct deposition of N to the surface waters of the Corsica River estuary from rainfall (atmospheric deposition of P is quite small and was not included)[19], sewage inputs from the town of Centerville, MD[20], and septic system leachate from systems located adjacent to tidal waters (septic system leachate not adjacent to tidal waters is captured in the diffuse source measurements).

What Are The Major Nutrient Sources?

The message is clear for both N and P inputs to the Corsica River estuary; diffuse sources are by far the largest single source (84% for N and 74% for P; Table 1). The second largest N source is storm water run off from the urbanized area of Centerville (10% for N and 25% for P). Atmospheric deposition of reactive N in rainfall directly on surface waters of the Corsica represented about 5% of all N inputs. Point sources (i.e., discharge from the Centerville sewage treatment plant) had formally been a significant source of both N and P prior to 2005. Before the new system went into operation, point source loads averaged about 1100kg /month of N and about 100 kg/month of P and those rates would have been the second and third largest sources of N and P, respectively.

Table 1: Summary of average total nitrogen and total phosphorus loads to the Corsica River estuary from all sources. Data are mainly from 2007. See Appendix for data sources and details concerning estimation procedures[18].

Nutrient Source	Total Nitrogen Load (kg N per month)	Total Phosphorus Load (kg P per month)
Diffuse Sources	8099 (82%)	1002 (73%)
Stormwater Runoff	1023 (10%)	345 (25%)
Direct Atmospheric Deposition	452 (4%)	~0 (0%)
Point Sources	168 (2%)	17 (2%)
Septic Leachate	149 (2%)	~0 (0%)
Total Load	**9891**	**1364**

However, since 2005, sewage discharges have been well-treated at the sewage plant to remove much of the N and P and then pumped to a large holding pond and sprayed on agricultural fields during periods of the year when the ground is not frozen. Currently, point source N and P loads represent only 1.7 and 1.2% of the total loads, respectively and are delivered to the Corsica mainly during winter months. The final input evaluated was the septic tank leachate term. In this evaluation, only septic tanks located adjacent to tidal waters were counted and the N loads estimated. These were found to be quite small (1.5% of the total N inputs) overall but may have very localized water quality impacts of some significance. While a good deal of P is associated with septic tank leachate, virtually all of this is quickly adsorbed by oxidized iron in soils and does not move with the groundwater to streams. There are about 809 septic systems operating in the Corsica watershed and about 160 are adjacent to tidal waters or very close to tidal waters. The N load associated with the non-tidal water septic systems (649 systems) is estimated to be about 610 kg N/month and this N is captured in the diffuse load.

When are N and P Loads Highest?

There is some important seasonality associated with both N and P loads to this estuary[21]. Additionally, loads can be influenced by large storm events at any time of the year. The largest N and P source (diffuse run off) appears to be greatest during winter-spring, often smaller during the summer period (if no large storms occur) and increasing again through the late fall. Storm water run off follows the same pattern but is considerably smaller in magnitude. Point sources are essentially zero during the spring through fall because of the treatment scheme used in this estuary, but were present (and relatively small) during January-February and December of 2007. Atmospheric deposition followed the opposite pattern with inputs being somewhat larger during the spring-summer periods. Overall, inputs are generally higher during winter-spring than during the summer-fall periods. Many of the estuaries, both big and small, of the Chesapeake follow this pattern.

Large storms can have a significant effect on nutrient loads, especially from diffuse and stormwater sources. During summer of 2006 there were several large rain events and loads increased sharply in June and, to a lesser extent, in July[21]. TN and TP loads to the Corsica River reached annual peaks in June, because of storms, rather than in the late-winter and spring as is typical. The exact impacts of temporal shifts in nutrient load delivery are not well understood at this time. In the Potomac River estuary, there are indications that early winter loads do not generate large phytoplankton blooms, possibly because light and temperature are controlling phytoplankton growth at that time of the year. In addition, early summer maximum loads do not cause as severe hypoxia in deeper systems, possibly because much of the organic matter generated from plankton blooms is decomposed rapidly at higher temperature above the pycnocline. The effects on the Corsica of temporal shifts in load delivery are not clear at this point, but they may be important because there is high algal biomass in winter at all stations, but summer algae appear to be responsible for the observed summer hypoxia.

How are Nutrient Loads Related to Nutrient Concentrations?

In the Corsica River estuary, as well as in Chesapeake Bay and its major tributaries, nutrient loading is strongly related to nutrient concentrations within the estuary (Figure 9)[23]. This robust relationship indicates the strong role of nitrogen loading in regulating the availability of inorganic nutrients (most of the new nutrient inputs from the land are as dissolved inorganic nutrients) and also reflects the use of these nutrients in algal biomass (much of the nitrogen in the estuary is in particulate or dissolved organic forms).

This sort of simple relationship is not readily found if loads are regressed against just DIN, because DIN or DIP is rapidly incorporated into algal biomass. But, it is important to know that there is a strong signal showing that nutrient loading rates are reflected in the total nutrient mass in the estuary and that this relationship seems to hold for both large and small estuaries of the Chesapeake (Figure 9).

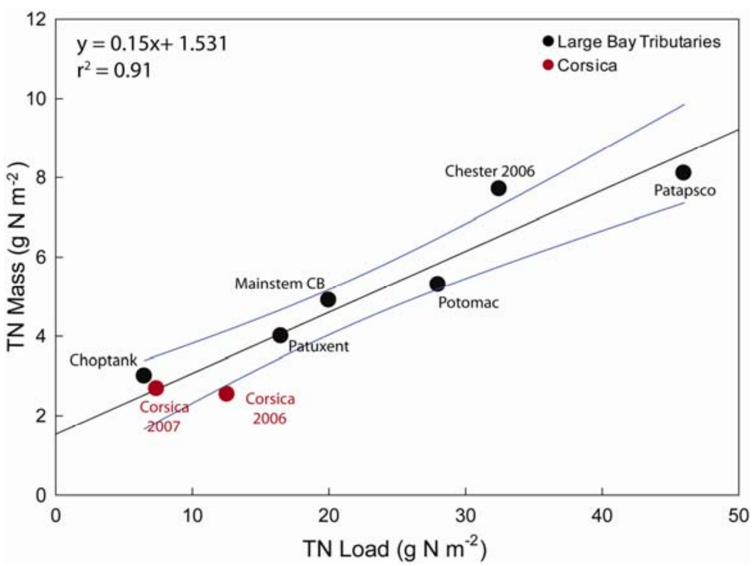

Figure 9: Annual total nitrogen load versus total nitrogen mass in surface waters for Chesapeake Bay and selected tributaries (decade mean), with January to May Corsica River data included for 2006 and 2007 (red circles).

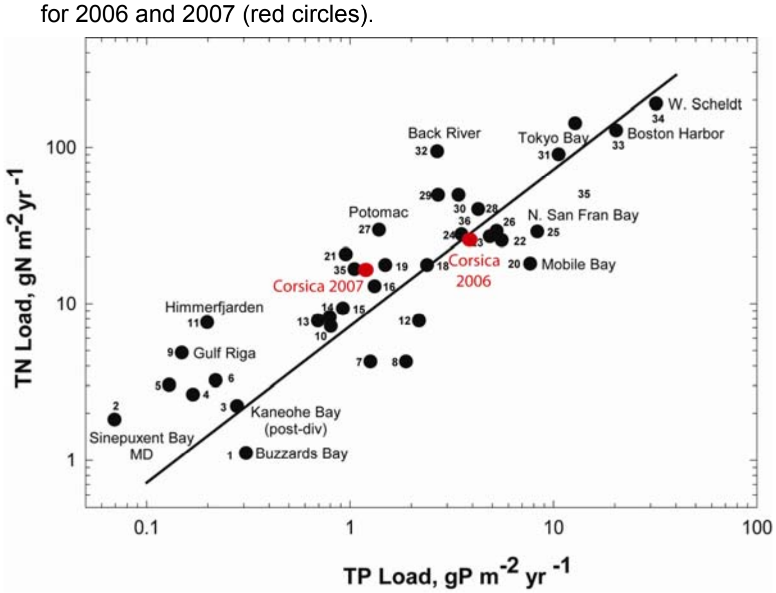

Figure 10: Annual total nitrogen versus total phosphorus loads for various estuarine systems, with Corsica River estuary estimates included (red circles) for 2006 and 2007. Nitrogen and phosphorus loads were 1.6 and 3.2 times higher in 2006 than 2007. In many Chesapeake Bay tributaries inter-annual loads vary between wet and dry years by factors of 2 to 3. See item 24 in Appendix for detail.

How Do Corsica N and P Loads Compare with Those in Other Estuaries?

Among 35 other estuarine systems, annual nutrient loading rates from adjacent watersheds ranged over several orders of magnitude, from 1.1 to 188 g N m^{-2} yr^{-1} and from 0.1 to 32 g P m^{-2} yr^{-} (Figure 10)[24]. The 2006 and 2007 average loads of TN and TP to the Corsica River estuary ranged from 17-27 g N m^{-2} yr^{-1} and from 1.2-3.8 g P m^{-2} yr^{-1}, which is moderate compared to the other sites.

Multi-year TN and TP input data for a few estuaries indicate that inter-annual variability can be large, but is not as large as the variability among all these systems. For example, TN and TP loads to the Guadaloupe estuary in Texas varied by factors of 3.7 and 2.5, respectively, in wet versus dry years. In comparison, TN and TP loads to the Patuxent varied by factors of 2.0 and 2.6, respectively. Kaneohe Bay, HI is an example where significant loading reductions in TN and TP (2 and 4.5-fold, respectively) resulted from a diversion of wastewater out of the Bay.

Among the same 35 estuaries, N: P ratios (mass basis) of inputs ranged from 2 to 38, bracketing the Redfield ratio (N: P = 7.2:1 mass ratio). About a quarter of these locations

(9 of 34) had load ratios that were considerably lower (< 5.0) than the Redfield ratio, while 50% (18 of 34) had ratios equal to or higher than 9.0. The average annual ratio for Corsica River was 7.3, which is relatively close to the Redfield ratio. Although point-source-dominated systems tend to have lower load ratios (sewage is rich in P relative to N), this is not always the case. For example, several systems (Himmerfjargen in Sweden, Back River in Maryland) had very high load ratios (38:1) even though point sources were the dominant nutrient source because P (and not N) was removed from sewage treatment plant effluent. The importance of the Redfield ratio is that it can serve as a crude guide indicating which nutrient (N or P) may be limiting algal production (N:P *mass* < 7 suggests possible N-limitation and N:P *mass* > 7 suggest possible P-limitation). In the case of the Corsica River estuary, an N:P ratio of about 7 indicates a balanced nutrient supply relative to the needs of phytoplankton and further suggest the need for a dual (N and P) nutrient control program. In fact, information presented earlier in this report indicates that both N and P concentrations in the Corsica are still very high relative to the growth needs of phytoplankton and would need to be greatly reduced before N or P would become limiting to plankton growth rates. These patterns of nutrient limitation conform to those previously reported for Chesapeake Bay and tributary rivers[25].

Finally, the estuarine literature indicates that comparable nutrient loads in different estuarine systems do not necessarily produce the same responses. For example, N loading rates in the Potomac River and Narragansett Bay are similar but poor water quality conditions are far more extensive in the Potomac than in Narragansett Bay. Factors like estuarine morphology, water circulation patterns, and regional climate conditions have strong influences on the relative importance of nutrient loading rates. In short, the degree of eutrophication experienced in an ecosystem like the Corsica River is modified by factors in addition to nutrient loading rates.

NUTRIENT FATES

For most estuaries, the Corsica included, there are four major pathways through which nutrients are lost from the ecosystem (Box 1). These include: (1) denitrification[26], a natural bacterial process mainly occurring

Box 1: Descriptions of nutrient loss pathways in the Corsica and other estuaries.

Denitrification:

- A natural bacterial process that occurs mainly in estuarine and marsh sediments
- A class of bacteria use nitrate (NO_3) in place of dissolved oxygen
- These bacteria convert nitrate to di-nitrogen gas (N_2) and this gas goes back to the atmosphere (78% of atmosphere is N_2 gas)
- So, this process converts a very biologically active form of nitrogen to a form that is biologically inert
- There is no equivalent biological removal process for phosphorus

Nutrient Burial:

- This is a natural process where the dead bodies of small plants and animals are buried in estuarine and marsh sediments
- Estuaries like the Corsica are filling in with sediments from shore erosion and upland soil loss. This is the material that "buries" the N and P.
- Some of the N and P is recycled before burial but in estuaries with lots of sediment (like the Corsica) significant amounts of N and P are buried each year)
- Once buried, these nutrients are effectively lost from daily use by plant and animal communities

Exports:

- Tidal action connects different portions of estuaries, transporting not only water but also dissolved and particulate materials in the water
- In the Corsica this transport of materials is mainly from the Corsica to the larger Chester River and represents a loss of N and P from the Corsica
- In some estuaries (like the Patuxent River) nutrients are no longer exported to Chesapeake Bay but are imported from the Bay to the Patuxent representing a reversal of a loss term

in estuarine, marsh and wetland sediments, (2) long-term burial of N and P in these same environments, (3) export of nutrients out of the ecosystem, normally to the next downstream system (i.e., the Chester River in this case), and (4) nutrient accumulation within the estuary via processes like increased benthic or fish biomass, enhanced SAV biomass, or as increased water column nutrient concentrations. These increases in nutrient storages during short periods of time (several years in this case) are not very important in other Chesapeake systems and, because of this, were not evaluated here.

What Do These Nutrient Budget Terms Mean?

A nutrient budget is a quantification of all inputs to, outputs from, and internal storage changes within an ecosystem. The utility of such budgets is that we can (1) track the movement of key nutrients through the system, (2) determine if we can balance the budget, (i.e., accurately quantify all the input and output terms), and (3) discover previously underappreciated terms, or errors in the known terms, if the budget does not balance. Nutrient *sources* refer to inputs of nutrient to the Corsica estuary from the adjacent watershed via streams and runoff, groundwater, the atmosphere, and from connected water bodies. In contrast, nutrient *fates* are losses, or outputs of nutrients from the system. These outputs are assumed to be permanent over the timescale of the calculation (1-2 years, at least). Temporary storages in the system, such as nutrient retained in the sediment surface or in water column particulate material, are assumed to be unchanging over the course of the budget calculation. Such an approach has been determined to be appropriate, based on previous budgeting experiences. Further information about these terms is provided in Box 1 and brief descriptions are provided below and in the glossary.

Denitrification and Long-Term Nutrient Burial

Denitrification measurements were made in deep and shallow portions of the Corsica estuary and in wetlands and streams at the head of the estuary to ensure all of the habitats where denitrification was likely to be occurring were represented[27]. Nitrogen losses due to denitrification were somewhat higher in the lower estuary than the upper estuary

Table 2: Summary of sediment denitrification[1] rates in the upper and lower Corsica River estuary and in the marsh/creek complex at the headwaters of the estuary.

Location	Denitrification Rates: Warm Season (May-Oct) (μmol N m^{-2} h^{-1})	Denitrification Rates: Cold Season (Nov-Apr) (μmol N m^{-2} h^{-1})	Annual Denitrification Losses (g N m^{-2} y^{-1})	Total Denitrification (kg N estuarine $zone^{-1}$ y^{-1})
Upper Corsica	68	34	6.2	6428
Lower Corsica	91	46	8.4	29123
Corsica Marshes[2]	264	132	24.3[3]	3694
			System Total	**39244**

[1]Denitrification is a naturally occurring bacterial process where a biologically active form of nitrogen (nitrate; NO_3) is transformed into di-nitrogen gas (N_2) a biologically inactive nitrogen form. The N_2 gas formed from denitrification goes back into the very large atmospheric pool of N_2. [2]The marsh creek complex represents only 3% of the full estuarine system but represents about 10% of all denitrification activity. This process is a major nitrogen loss term in this estuary. [3]Note that a denitrification rate of 24.3 g N/m^2/yr is equivalent to 217 pounds of N/acre/year.

(Table 2) but rates in both locations were substantial relative to losses documented in other estuarine systems. However, losses in the wetlands were over three times those measured in the estuary (Table 2), again indicating the importance of these habitats in maintaining and protecting good water quality. When these rates of denitrification are pro-rated over the open waters of the estuary and wetlands about 39000 kg N/year are removed by this process. This represents about one third of all the nitrogen entering the Corsica River estuary and thus represents an important "self-cleansing" property of the estuary. Others have found that in less nutrient stressed environments, as much as 50% of all nitrogen inputs were lost to denitrification[26].

Table 3: Summary of sediment nitrogen concentrations, sedimentation rates, and surface and deep burial of nitrogen in the upper and lower Corsica River estuary.

			N Burial		
	PN Concentration[1]	^{210}Sedimentation Rate	Surface[1]	Deep[2]	Total
Location	g N/kg dry sediment	kg dry sediment m^{-2} y^{-1}	g N m^{-2} y^{-1}	g N m^{-2} y^{-1}	kg N est. $zone^{-1}$ y^{-1}
Upper Corsica[3]	4.5	3.1	14.1	9.9	10223
Lower Corsica[4]	3.0	1.5	4.6	3.2	11083
				System Total	**21306**

[1]Particulate nitrogen concentrations were measured in the surface 1 cm of the sediments. Surface burial estimates used these values coupled with sedimentation rates. [2]Deep N burial, which represents a far more permanent loss of N from the system, was estimated using 70% of surface nitrogen values reflecting the fact that some of the surface nitrogen was remineralized and not buried. [3]The area of upper Corsica estimated to be 1036700 m^2; [4]area of lower Corsica estimated to be 3467027 m^2. These areas correspond to the surface areas used in the box model. The deep burial estimate of 9.9 g N/m2/yr is equivalent to 88 pounds of N/acre/yr.

Long-term burial of nitrogen also turned out to be an important loss term[28]. The nitrogen burial rates in the upper Corsica were about three times as high as in the lower Corsica because sedimentation rates in the upper Corsica were quite high compared to those in the lower Corsica (Table 3). Sedimentation rates in the Corsica are comparable to those measured in other tributaries of Chesapeake Bay and other coastal systems (see Table 4[29]). The use of several isotopes in Corsica River studies allowed geologists to determine that most of the sediments in the upper Corsica were derived from stream inputs from the basin, the mid-Corsica sediments from shoreline erosion and the lower Corsica from a combination of shoreline erosion, and inputs from the Chester River. When burial rates are pro-rated over the full Corsica River estuary, results indicate that about 21000 kg N/year are buried in sediments of the estuary. This loss represents about 18 percent of all nitrogen entering the Corsica River system.

Nutrient Losses to the Chester River Estuary

One of the difficult but important terms needing quantification in nutrient assessments such as this Corsica evaluation, involves estimating the tidal exchange of materials between the estuary of interest (the Corsica in this case) and the adjacent downstream system (the Chester River)[30]. Tides move water into and out of the Corsica and along with this water moves nitrogen, phosphorus, sediments and other suspended and dissolved materials. To make this estimate, a water and salt balance model (often called a box model) was developed and used to compute the flux of water in and out of

Table 4: Summary of long-term particulate nitrogen (PN) burial rates for several tidal marshes and a selection of estuarine ecosystems.

Ecosystem Type	Location	N Burial Rate[1] (g N m^{-2} y^{-1})
Tidal Marshes	N. Carolina	2.7
	Louisiana	21.0
	N. Carolina	8.5
	Choptank River, MD	23.0
	Monie Bay, MD	14.0
	Patuxent River, MD	21.0
	Hudson River, NY	9.0
	Delaware Bay	2.5
Estuaries	Chesapeake (oligohaline)	11.0
	Chesapeake (mesohaline)	3.5
	Patuxent River, MD (oligohaline)	14.0
	Patuxent River, MD (mesohaline)	5.0
	Potomac River (mesohaline)	10.0
	Choptank river, MD (mesohaline)	1.7
	Delaware Bay	1.1
	Narragansett Bay, RI	3.3
	Guadalupe Bay, TX	0.5
	Ochlockonee Bay, FL	1.6
	Boston Harbor, MA	2.6
	Scheldt, Holland	14.0

[1]Methods used to determine PN burial rates varied, but all included an estimate of sediment accumulation (^{210}Pd, sediment budget, pollen grain analysis) and an estimate of PN concentration at a depth in the sediment column where concentrations were constant over depth.

the estuary (details of this computation are provided in a reference cited in this report's Appendix[30]). These water flows were coupled to nutrient concentration measurements and net exchanges of N and P were made on a monthly basis. Unfortunately, data gaps limited such estimates to only a portion of the year (May–October). To obtain annual export estimates of TN and TP exchange between the Corsica and Chester, daily average export of TN and TP were computed and scaled up to a full year. TN and TP exports from the Corsica to the Chester were about 51000 kg N/year and 13000 kg P/year representing about 43 and 79% of all TN and TP inputs to the Corsica system (Figure 11). Thus, export was an important loss term for nitrogen and a dominating loss term for phosphorus.

Synthesis of Nutrient Sources and Fates:

One test for the veracity and consistency of this analysis is to examine the overall balance between inputs and outputs of TN and TP mass. Nutrient budgets in the context of estuarine research are an application of the conservation of mass laws. The constraint that mass must be conserved is the foundation of budget analysis. Budgets that balance (inputs = outputs) lead us to believe we have a solid understanding of the system while those that do not balance by a wide margin send us back to the drawing boards because we have missed something important. A nitrogen budget for the Corsica River estuary is provided in Figure 11 where the red bars indicate various N inputs to the ecosystem and the blue bars represent nitrogen losses from the system. This budget assumes (1) steady state, (2) completeness (i.e., there are no missing terms in the budget), and (3) internal storages that are unaccounted for are not changing from year to year. There are several key issues that are resolved by inspecting this diagram. First, the budget is close to being

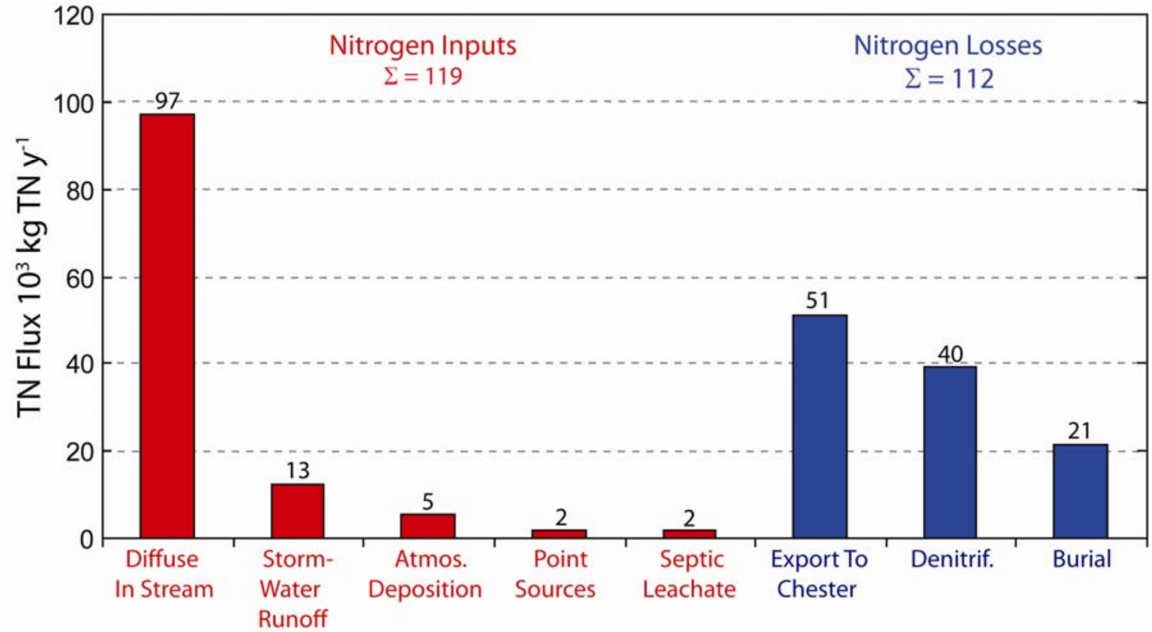

Figure 11: Annual total nitrogen budget for the Corsica River estuary for 2006, except for estimates of N export to the Chester River, which are a May-October average extrapolated to entire year. Budgets include measured input fluxes from the atmosphere and watershed, while nitrogen transport between the Corsica River and the Chester Rivers are derived from box model estimates. Storm water runoff is only from the town of Centreville. Septic leachate estimates are for regions of the watershed that are adjacent to tidal waters that are not gauged. Denitrification and nitrogen burial in subtidal sediments and upper estuary tidal marshes were directly measured in the Corsica. Note that nitrogen losses come close to balancing nitrogen inputs. Refer to the glossary for definitions of budget terms.

balanced. TN inputs (119000 kg N/year) are close to the measured nitrogen losses (112000 kg N/year) indicating that major processes have been adequately considered.

The second point is that diffuse sources are by far the most important nitrogen source. Efforts to improve water quality will likely fail unless this term is sharply reduced. Third, the nitrogen loss terms are all important, with export to the Chester River being the largest. This export represents another nutrient source to the Chester, an estuary also suffering from nutrient over-enrichment. There is reason for concern here. Should nutrient concentrations in the Chester increase further, or if remediation reduces N concentrations in the Corsica (so they are less than those in the Chester), the direction of this process could change and the Chester could become another nutrient source to the Corsica rather than a nutrient sink. This reversal of nutrient flux has already been documented for the Patuxent River estuary and the Chester River is already a source of inorganic nitrogen (NO_3^-) to the Corsica in some summer and fall months. It is possible that the Chester River may become a real nutrient source to the Corsica River as remediation proceeds.

Currently, denitrification represents a nitrogen loss amounting to about 34% of all nitrogen inputs. In estuarine ecosystems that are less nutrient stressed researchers have found that 40-50% of all nitrogen inputs are lost via denitrification. A similar increase in the relative importance of denitrification as a nutrient loss term might occur after nitrogen loads to the Corsica decrease, further improving water quality. At this point the message from the nutrient budget seems clear; successful restoration depends on sharp reductions in diffuse source nutrient inputs.

INCREASED N-INPUTS CAUSE MORE ALGAE IN THE ESTUARY

Similar to many estuarine and coastal ecosystems, excessive nutrient loading is the primary cause of rapid algal growth and biomass accumulation (algal blooms measured as chlorophyll-a concentration) in the Corsica River estuary. This relationship between nutrient loads from all sources and algal responses (in terms of chlorophyll-a concentration) is a critical starting point for the analyses that follow in this and the following sections. Essentially, a simple cause-effect chain is developed, where the nutrient loading from drainage basins is linked to estuarine chlorophyll-a, which is subsequently linked to summer water clarity and hypoxia. These linkages of key water quality issues to nutrient loads and chlorophyll-a will allow for estimates of the likely magnitude of estuarine responses to nutrient load reductions if and when they occur.

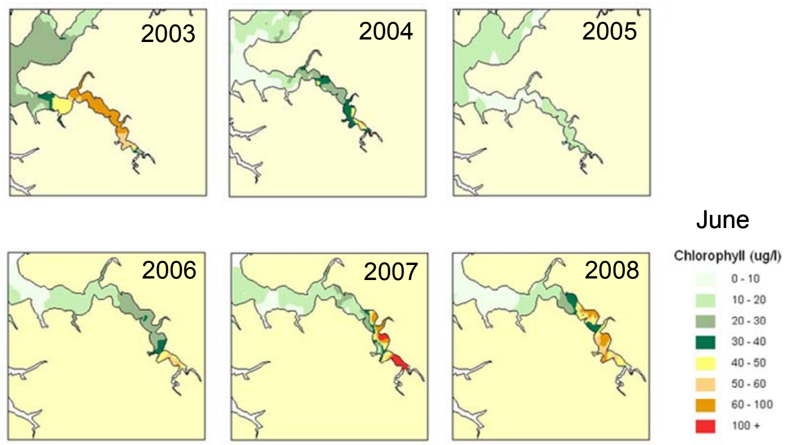

Figure 12: Time series of June chlorophyll-a distributions in the Corsica River estuary as measured during DATAFLOW cruises. There is considerable inter-annual variability in chlorophyll concentrations likely reflecting differences in nutrient loading rates between wet (2003) and dry (2005) years. Other factors, such as light availability, also certainly come into play. However, in all years highest concentrations were measured in the upper portion of the estuary, closest to major nutrient sources. Data are from the MD DNR Dataflow Program. Note that 2003-2005 figures include a small section of the Chester River.

Intensive and repeated measurements of chlorophyll-a distributions throughout the Corsica indicated the most elevated chlorophyll-a concentrations occurred during years with the highest stream flow (and associated nutrient load), with a few exceptions (e.g., 2008). The most intense algal blooms (e.g., June, Figure 12[31]) typically occurred in the upper estuary, landward of Alder Branch (Figures 2, 4) adjacent to the streams carrying most of the nutrient load to the estuary. Although continuous measurements of chlorophyll-a clearly indicate that the biggest algal blooms in the Corsica occur during the January-May period, summer concentrations are responsible for hypoxic events. The crash of winter-spring algal blooms deposits large amounts of labile organic material onto sediments, which are not decomposed until early-to-mid summer when elevated temperature stimulates bacterial activity. Respiration of such material releases nutrients to the water column during summer and these nutrients help stimulate the summer blooms in the Corsica estuary. As a result, spring chlorophyll-a concentrations are highly correlated with summer chlorophyll-a at all three Corsica CONMON stations.

This connection of winter-spring nutrient loads to summer blooms is well described in Chesapeake Bay and its tributaries and is also reflected in data for several shallow estuaries connected or adjacent to Chesapeake Bay region. In a multi-system comparison of shallow, eutrophic estuaries in the region of Chesapeake Bay, spring N loading and summer chlorophyll-a were found to be highly correlated, and available data for the Corsica River estuary fit the general pattern (Figure 13[32]). Correlations between winter-spring nutrient load and summer chlorophyll-a is not linear and indicates the potential for large declines in chlorophyll-a in response to nitrogen load reductions between 0.2 to 0.05 g N m^{-2} d^{-1} (Figure 13). The Corsica River estuary currently exists near this potential nitrogen load "tipping point".

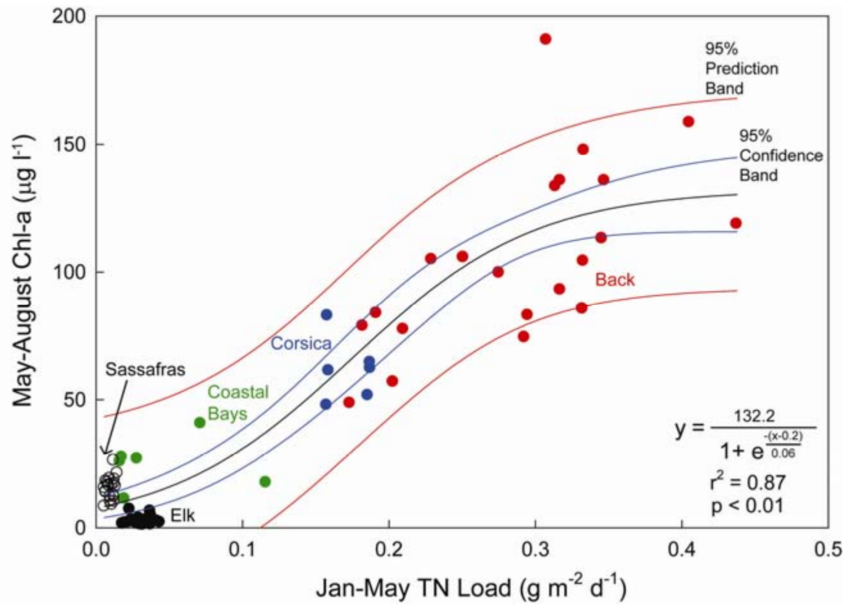

Figure 13: Relationship of winter-spring TN loading to summer chlorophyll-a in several shallow, well-mixed estuaries in the Chesapeake Bay region, including the Corsica River estuary.

In summary, the largest algal blooms occur in the winter-spring period when nutrient loads from the watershed are highest. Summer algal blooms are largest in the upper estuary adjacent to the major streams that drain the watershed and deliver a large fraction of the nutrient load. Finally, using data from the Corsica and several other eutrophic Chesapeake Bay tributaries a strong relationship was observed between nitrogen loading rates (winter-spring period) and summer algal bloom intensity. The combination of the non-linear relationship and the present position of the Corsica near the inflection point of the curve suggest that a 50% reduction in N loading to the estuary would produce a 70% decline in chlorophyll-a.

INCREASED ALGAE CONTRIBUTES TO DECREASED WATER CLARITY

Water clarity determines how much sunlight penetrates through the water and is available for photosynthesis by phytoplankton in the water column and by SAV and benthic algae growing in the sediments. Water clarity is typically reduced in estuaries when the concentration of algae, sediments, and other particles increases in the water column and that is clearly the case in the Corsica River estuary.

A device called a Secchi Disk[33] was used to measure water clarity throughout the estuary during the spring-fall periods. These measurements revealed distinct patterns in water clarity for the Corsica River estuary. First, water clarity was poor throughout the estuary. Secchi depths very rarely exceeded one meter at any station during any month (Figure 6). Second, water clarity increased from the head waters of the estuary to the mouth, a pattern seen in many other estuarine systems. The upper estuary is closest to land-derived sediment and nutrient sources and is the area with the most intensive algal blooms, both of which serve to decrease water clarity. Finally, water clarity throughout the estuary was greatest during fall, a period of reduced water inflows from the basin and decreased algal blooming.

Using Secchi Disk[33] information, it is possible to estimate the water depth to which 1% of surface light penetrates. This is of significance because 1% of surface light is the minimum light level needed to support growth of benthic micro-algae (e.g., benthic diatoms). Growth of these algae on the sediment surface can reduce nutrient flux from sediments (good for water quality) to the water column and also suppress sediment resuspension (good for water transparency). Using the mean depths of the estuary along its axis and the depth of 1% light penetration, it is clear that most areas of the Corsica River estuary, despite very shallow depths (< 2.5 m), are aphotic (in the dark). It is only in the very shallow (and very turbid) upper estuary that some light gets to the bottom.

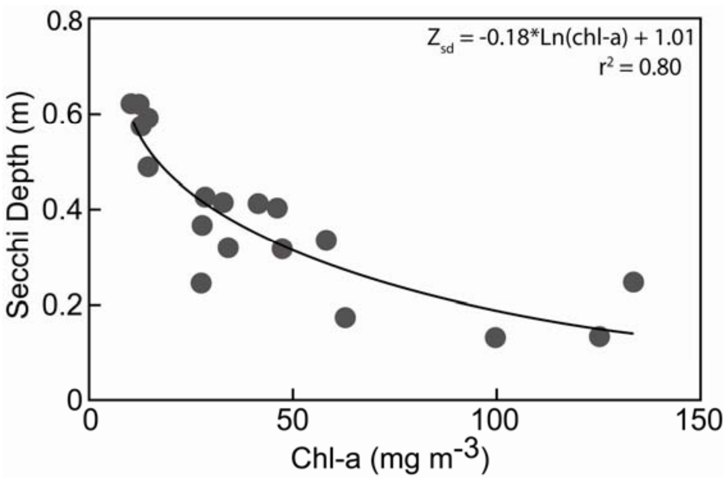

Figure 14: Relationship between Secchi depth and chlorophyll-a at all stations in the Corsica River estuary during 2006.

Correlations between Secchi depth and both chlorophyll-a and Total Suspended Solids (TSS) suggest that both contribute to light attenuation in the Corsica River estuary[34], but chlorophyll-a exerts a stronger control on water clarity (Figure 14). Take for example that concentrations of chlorophyll-a at about 100 mg m^{-3} generate Secchi depths of only 0.18 m, whereas chlorophyll-a concentrations reduced to 20 mg m^{-3} were associated with Secchi depths of about 0.5 m, a nearly four-fold increase in Secchi depths. Additionally, because chlorophyll-a and TSS may interact when algal exudates flocculate inorganic materials together, TSS concentrations may represent the combined light attenuation of algal and inorganic particles. Thus, computations of phytoplankton dry weight (W_p) provide a specific measure of phytoplankton contributions to TSS[2]. Our calculations indicate that W_p generally represents 10-30% of the TSS pool in the upper and lower Corsica, while in certain months (Sept. and Oct.) W_p can be as much as 50% of TSS[2]. We therefore conclude that both phytoplankton and inorganic particles contribute significantly to light attenuation, and that reductions in chlorophyll-a via nutrient load reductions would result in increased water clarity in the Corsica estuary.

To place the water clarity issue at the spatial scale of the whole estuary, bathymetric data were combined with Secchi data to examine the percent of light reaching the bottom of the estuary (<1%, 1-15% and >15% of surface light; Figure 15). At Secchi depths of 0.5 m (slightly clearer water than currently observed in most of the Corsica) only 10% of the estuary bottom had sufficient light to potentially support SAV communities and only about 28% of the bottom received enough light to support benthic algae.

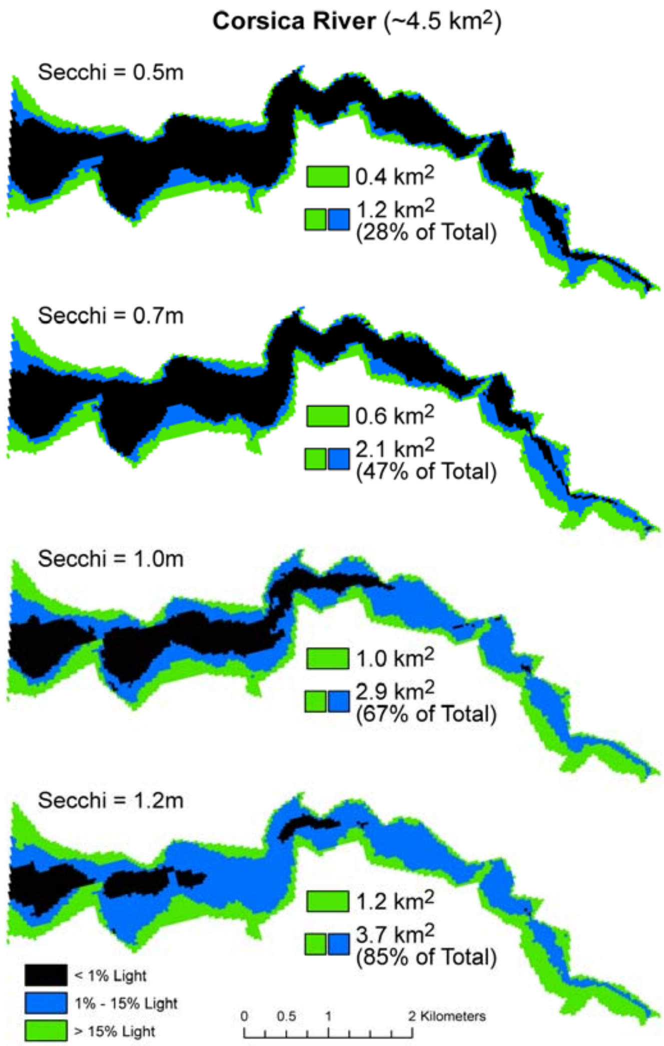

Figure 15: Area of the Corsica River estuary receiving <1 % of surface light (plant growth inhibited), 1-15% of surface light (benthic algal can grow), and >15% surface light (SAV can grow) at various water clarity conditions as measured by Secchi depths. Note the sharp increase in lighted bottom area associated with a change in Secchi depth from 0.7 to 1.2 m.

However, if the water column was clearer (Secchi depth = 1.0m) than the entire upper portion of the estuary would have at least 1% of light reaching the bottom and more than half the lower estuary would have 1% of surface light reaching the bottom. The important point here is that a relatively small change in water clarity (Secchi depths increase by ~0.5 m) would greatly increase the area of bottom receiving 1 % light (28% versus 67% of the bottom area).

INCREASED ALGAE CAUSES LESS DISSOLVED OXYGEN

The final link between nutrient loads and water quality involves establishing significant, quantitative relationships for phytoplankton chlorophyll-a and hypoxia or low dissolved oxygen (O_2) conditions, which are harmful to animal life[35,37]. There were a huge number of oxygen measurements made since 2005 at three primary locations in the Corsica River estuary (upper, mid and lower estuary) using multi-probe sensor systems that recorded dissolved oxygen and other variables every 15 minutes between March and October of each year. Thus, at each of these sites approximately 21000 O_2 measurements were collected each year (2005-2008). In shallow estuarine systems like the Corsica River, large phytoplankton blooms occurring during summer cause large dawn to dusk changes (10-20 mg l^{-1}) in O_2 during a single day. Such large daily swings in O_2 are caused by high rates of algal photosynthetic activity during the day (fueled by high nutrients), followed by high respiration rates (fueled mostly by simple carbohydrates produced by the day's photosynthesis) during the night. Night time respiration is often high enough in the Corsica River estuary to cause hypoxia ($O_2 < 2$ mg l^{-1}) throughout the entire water column. Corsica River data were analyzed to record all occurrences of hypoxia. The most frequent and intense hypoxic events occurred at Sycamore Point (Figure 16)[36].

On a few occasions, hypoxia was maintained for extended periods that were longer than 12-16 hours and continued into sunlit, mid-day periods. Statistical analyses of the O_2 data (using an approach called CART) indicated that these near full day hypoxic events occurred during days with seasonal peaks in water temperature (>28^{o}C), extremely cloudy conditions (PAR <20 μE m^{-2} s^{-1}), and calm wind speed (<4 m s^{-1} or 9 mph). Hypoxia was recorded during summer in all regions of the Corsica estuary during 2006 and 2007, but hypoxia was most intensive during June-August at Sycamore Point in the upper Corsica River estuary at the same location where algal blooms were most intense (Figure 12).

Summer chlorophyll-a concentrations were highly correlated with summer cumulative duration of hypoxia at all stations in the Corsica River estuary (Figure 16), suggesting a strong link between nutrient loading, algal biomass accumulation, and hypoxia. Consequently, it is anticipated that reductions in nutrient load will decrease both the duration and frequency of hypoxic events in the Corsica River estuary,

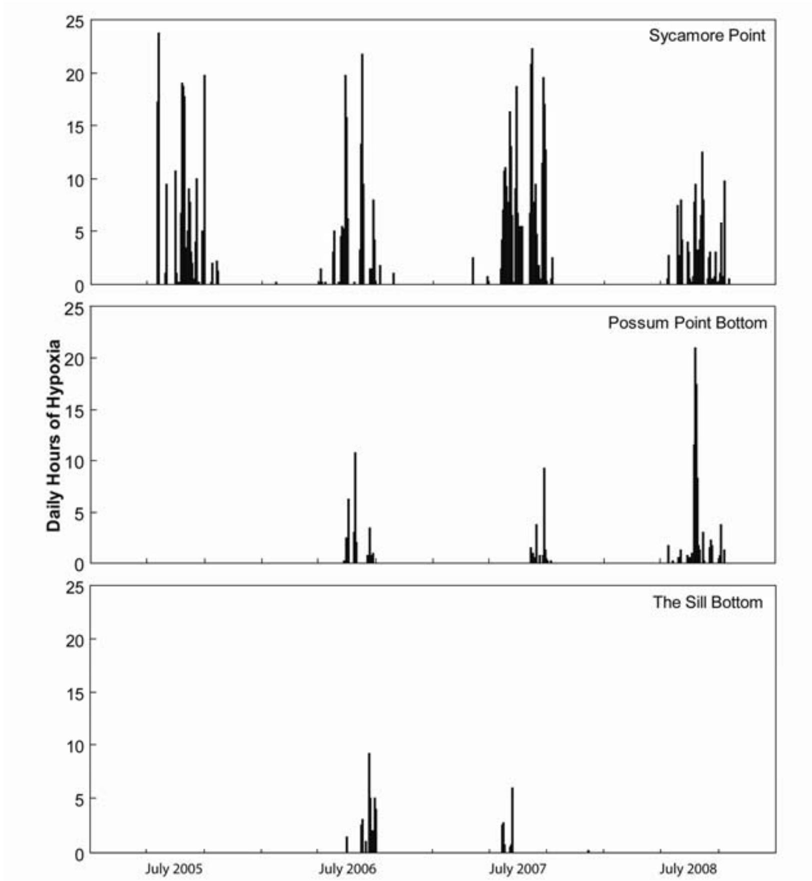

Figure 16: Daily hours of hypoxia at all Corsica River estuary stations (upper, middle and lower estuary CONMON sites; See Figure 2 for locations) from 2005 to 2008.

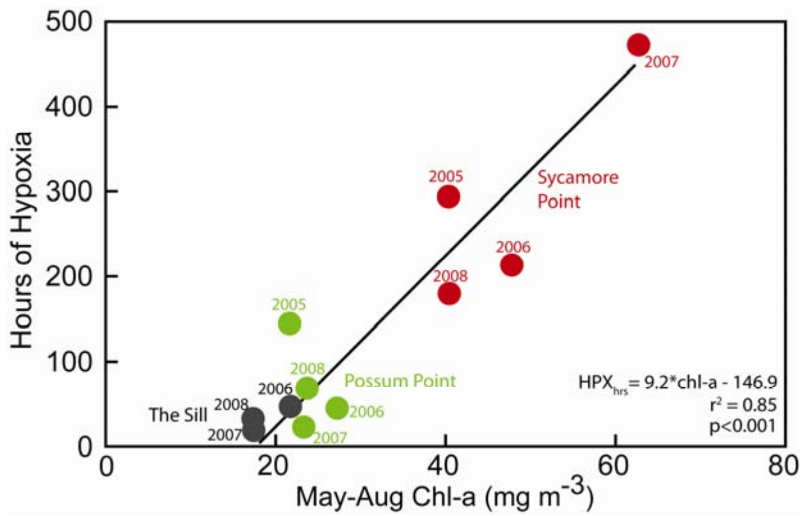

Figure 17: Correlation between summer chlorophyll-a and total summer hours of hypoxia at all Corsica River estuary stations (upper, middle and lower estuary CONMON sites; See Figure 2 for locations) from 2005 to 2008. Note that 500 hours is equal to about 3 weeks.

especially if May to August chlorophyll-a concentrations could be reduced to concentrations consistently below 20 mg m^3.

NUTRIENT MANAGEMENT SCENARIOS

This section of the report summarizes: (1) nutrient load reductions that appear possible (or have been completed) in the Corsica River watershed since 2005 (Table 5, Figure 19) and (2) responses of the Corsica River estuary to nutrient load reductions. The discussion includes expected non-linear responses of estuarine ecosystems to load modifications and lag times associated with groundwater nutrient storage.

Load Reduction Estimates

Here, we summarize and explain demonstrated or potential nutrient load reductions that are implemented or planned for the Corsica River watershed (Table 5)[38].

Atmospheric Reductions: In this scenario we did not make any adjustment for atmospheric deposition of nitrogen via local BMPs[39]. Atmospheric deposition is a very large scale issue (involving land areas much larger than the Corsica basin) and thus there are no local actions that would effectively reduce this nitrogen source. Phosphorus deposition from the atmosphere is very small and was not considered. While atmospheric deposition of nitrogen directly to the surface waters of the estuary was small (~5400 kg N/year), the same deposition occurs over the full 24000 acres of watershed and some portion of this deposited nitrogen reaches streams and is included in the storm water and diffuse run off input terms (Figure 11). Even modest reductions in atmospheric deposition of N would depend on a national-scale program of NO_x reductions from power plants and automotive exhausts.

Septic System Upgrades to Denitrifying (Pre-Treatment) Systems:[40] There are a reported 809 septic systems operative in the Corsica River watershed, about 160 of them adjacent to tidal waters. New denitrifying septic systems (also called pre-treatment systems) are capable of removing between 50% and 95% of the nitrogen leaving the septic tanks and going into leaching fields. If all homes served via septic systems were upgraded to an intermediate nitrogen removal level (~75%), the full septic system load to the Corsica (12100 kg/year) would be reduced to about 3030 kg N/year. A reduction of this magnitude would constitute about an 8% reduction in total loads. Should septic system upgrades be aggressively pursued, there would not be an immediate load reduction (as at a sewage treatment plant outfall) because septic system leachate moves through the groundwater system before reaching a stream and eventually the estuary.

Storm Water Control:[41] Storm water nitrogen loads evaluated here were associated with the town of Centerville. These loads enter downstream of the gauging sites on the Corsica stream network and were thus separately estimated. We estimated potential N load reductions using data developed from field-based measurements at the University of New Hampshire’s Storm Water Center. This Center tested a variety of devices with N removal efficiencies ranging from near-zero to almost 100%. Several had removal efficiencies of about 50% and we used this as an estimate of over-all potential removal efficiency. Among the systems tested were bioretention systems, gravel wetlands, retention ponds and various swale systems, most of which could be used in the Corsica basin. Using this approach, about 6200 kg N/year would be removed from the current load to the Corsica River estuary, representing about a 5% decrease in TN load. One aspect of storm water nutrient control differing from septic systems and other diffuse sources is that once the systems are built and functioning properly the load reduction is more immediate because there is no delay due to water transit through the groundwater system.

Agricultural Cover-Crops:[42] Since agricultural land is the dominant land use in the basin, the largest potential load reductions could be achieved by managing agricultural practices. We made several estimates of N load reductions based upon different levels of farmer participation in cover cropping (Table 5). The first estimate used just the area of land currently in traditional cover cropping programs (526 ha; 53% reduction efficiency) and this resulted in about a 5% reduction in nitrogen coming from croplands in the basin. The second estimate assumed general participation in cover cropping, but because of different cropping schemes only 33% of cropland would be cover cropped early in the fall (October; 1820 ha with 53% N removal efficiency), 33% of cropland would be planted late (November-December; 1820 ha with 23% N removal efficiency) and 33% of cropland would not be cover cropped at all. This scheme resulted in a 26% reduction in N from croplands. The final estimate assumed all cropland in the basin would be in early cover crops (5464 ha with 53% N removal efficiency). This scheme resulted in a 53% reduction in N from croplands and represents a large reduction in N loading to the Corsica River estuary (Table 5, Figure 19).

Lag Times and Quick Fixes in Load Reductions

When significant time and money are spent in nutrient reduction programs it is certainly worth asking "How soon will nutrient load reductions occur after these programs are operative?" In the case of the Corsica River it appears the most likely answer is *"not fast"* because so much of the nitrogen load is routed through the groundwater system where large water volumes and nutrient storages create significant lag times. There are no direct measurements of groundwater residence time for the Corsica River watershed, but in the nearby German Branch watershed groundwater residence times were measured and ranged from one to about 100 years with an average of about 18 years. This means that the water entering the groundwater system this year will, on average, reach a stream after an 18-year period. Thus, there is a substantial lag time between implementation of practices that reduce groundwater nitrogen concentrations and when that improved or low-nitrogen water enters the stream network and the Corsica estuary. However, those areas of the basin close to streams would respond more rapidly to BMPs, such as cover crops, than those areas distant from streams. Patience and persistence with cover cropping will be necessary to substantially decrease nitrogen loads from agricultural areas in the basin.

Table 5: A summary of current TN input rates (2006-2007) and potential rates based on estimated impact of Best Management Practices (BMPs) in the watershed. Details concerning development of these estimates are provided in the report appendix.

Total Nitrogen

Nutrient Source Category	Current Input Rate	Potential/Actual TN Load Reduction (kg N y^{-1})	Reduction in TN Input (kg N y^{-1})	Response Time
Atmospheric Deposition[1]	5400	~0	~0%	Months
Point Source, pre-2005[2]	12800	10800	84%	Months
Point Source, current[2]	2000	~0	~0%	
Septic systems[3]				
Adjacent to tidal waters	2400	1800	75%	Years-Decade
All other septic systems	9700	7300	75%	
Diffuse Sources[4]	87300			
With current cover crops		6100	5%	Years-Decade
With practical cover crops		31000	26%	
With maximum cover crops		64000	53%	
Storm Water[5]	12300	6200	50%	Months-Years

Pre-Small Water shed Program Load	129000
Current Total Load (2006-2007)	119100 (8%)
Reduced Load Expected from practical cover crops	**72800 (44%)**
Reduced Load Expected from maximum cover crops	**39800 (69%)**

[1]No change expected in atmospheric deposition of N. Any significant reduction likely would come from regional to national-scale reductions in N-emissions from power plants and automotive exhausts.

[2]The large (12800 kg N/yr) sewage treatment plant input was from the period prior to sewage treatment plant/wastewater lagoon system operation. The current loads (2000 kg N/yr) mainly occur during winter periods when the lagoon is filled and spray irrigation of effluent not possible. No further reductions are anticipated

[3]Septic systems were divided into two categories: 1) those adjacent to tidal waters (161 systems) where leachate would drain directly to the estuary and 2) those in the basin (648) where leachate would flow into streams draining into the Corsica River estuary. With current septic system denitrifying technology an N removal rate of 75% was used because this was intermediate between the least and most efficient N systems.

[4]Diffuse sources include surface and groundwater N loads from the Corsica basin but excluding stormwater flows from the town of Centerville. The diffuse source number in the table (87300 kg/yr) is 9700 kg/yr less than the value shown in Table 1 because non-tidal water septic loads were removed and counted separately in this evaluation. Reduction in N load from cover crops was estimated by dividing the diffuse load by the area of row crop agriculture in the basin, then applying a cover crop efficiency coefficient (0.40) developed by the Cover Crop Panel and MAWP and then multiplying this reduced load per area by the area of agricultural cropland (6071 ha). The same procedure was used to estimate current N load reductions due to current cover cropping (526 ha).

[5]Reductions in stormwater loads were estimated by examining the various stormwater management devices evaluated under field conditions by the University of New Hampshire's Stormwater Center. Bioretention systems, gravel wetlands, retention ponds and various swale systems indicated removal efficiencies of about 50%. Estimated storm water N loads were reduced by 50% in this evaluation

There is reason to believe that some management practices will produce favorable responses more rapidly. Certainly the upgrading of the Centerville sewage system represented a significant and rapid reduction in nutrient loads (Table 5). Similarly, we would expect that upgrading of septic systems to remove nitrogen (pre-treatment systems) in areas immediately adjacent to tidal waters would produce positive (but small) effects quickly because distances from septic fields to tidal waters is small.

A third possibility involves managing for nutrient runoff during high flow events. While the baseline nutrient concentration (and load) in a stream are primarily the product of groundwater loads (where long lag times may exist between nutrient management and a response), loads during high flow (storm) events are often fueled by nutrients washing off of streets, lawns, and fields. Using data on stream flow (hydrographs) with measurements of the concentrations of TN and DIN collected from the three major streams flowing into the Corsica, the percentage of the nitrogen load delivered via stormwater flows (which is equal to storm loads and baseflow loads) was computed for each season of the year (Figure 18)[43]. The significance of this partitioning of loads is that there is much less lag time related to stormwater flows as there is with pure ground water flows. Thus, reductions in storm water flows and associated nutrient concentrations would have immediate and positive effects on nutrient load reductions and water quality. The percent of nitrogen associated with storm water flows varied considerably. In general, storm water nitrogen loads were highest in spring, lowest in summer and intermediate in fall and winter. However, about 50% of springtime loading from Gravel Run and Mill Stream (Figure 4) were associated with storm or high flow events. Thus, if the potential for nutrient loading during storm events could be reduced using BMPs (via reduced nutrient concentrations), some significant load reductions could be achieved without serious lag-time effects. Such BMPs include cover cropping, buffer strips between farm fields and streams, lower fertilizer applications on lawns, parks, and fields, and better management of storm water in urban areas and suburban developments.

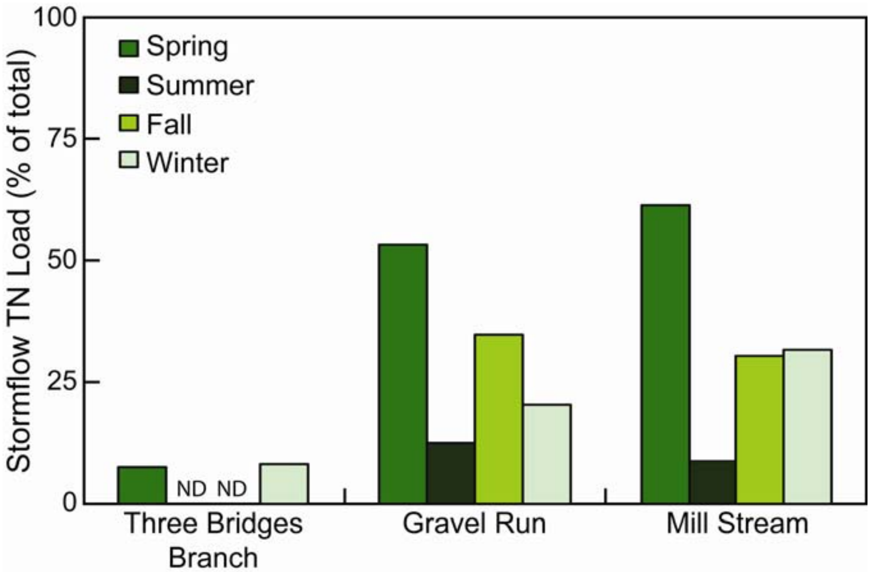

Figure 18: Comparison of stormflow versus baseflow TN loads at three streams discharging into the Corsica River estuary over four seasons in 2006 (ND = no data).

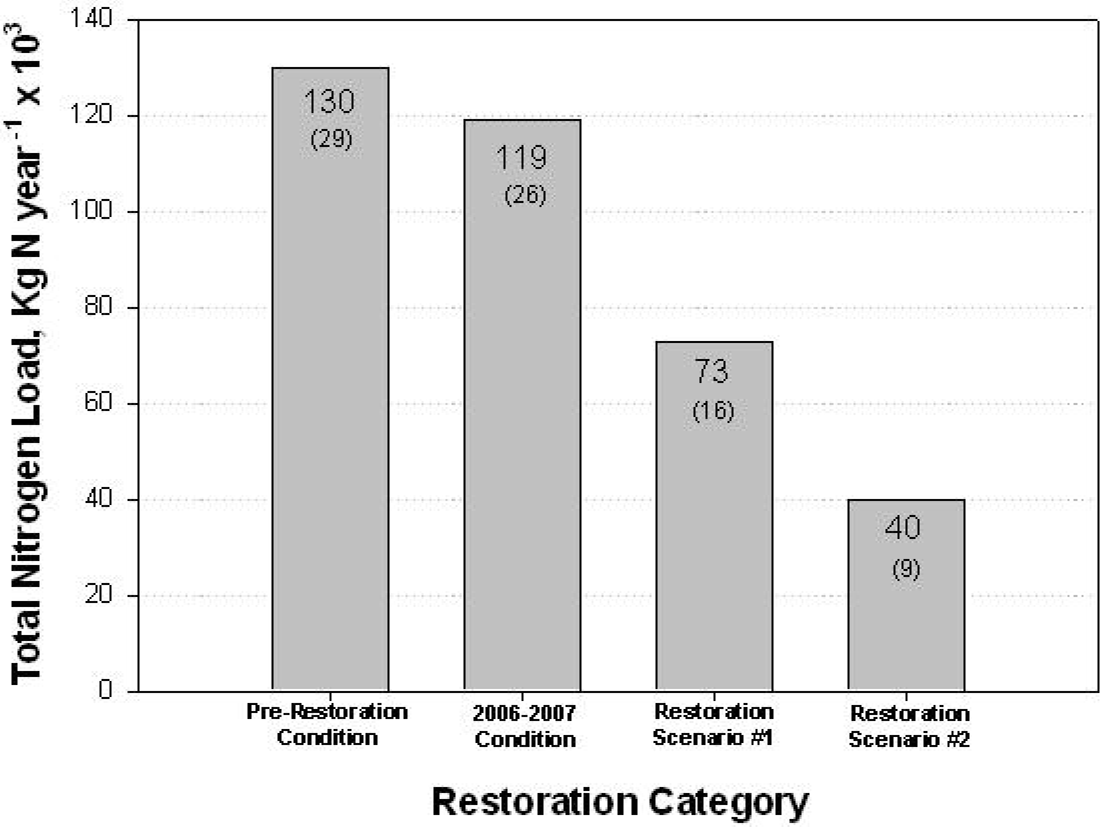

Figure 19: A simple bar graph indicating TN loads to the Corsica River estuary under different conditions. The Pre-Restoration condition refers to the period immediately prior to the up-grade of the Centerville sewage treatment plant (~2005). The 2006-2007 condition refers to the time period used in this analysis. Restoration Scenario #1 includes TN load reductions associated with installation of denitrifying septic systems at all homes served by septic systems, installation of storm water management structures and a cover crop program referred to as the Practical Option in Table 5. Scenario #2 includes the first two items in Scenario #1 and a cover crop program referred to as the Maximum Option in Table 5. The bold numbers in each bar indicate TN load (kg N year x 10^3); smaller numbers in parentheses (g N m^{-2} yr^{-1}) indicate areal TN loads to the estuary to facilitate comparisons with data presented in Figure 10. It is very likely that there are substantial lag times associated with both restoration scenarios (see text for explanations).

ESTIMATING ECOSYSTEM RESPONSES TO NUTRIENT LOAD REDUCTIONS

This analysis of land uses, nutrient loading rates, and estuarine biogeochemistry permit different approaches to computing likely ecosystem responses expected from nutrient load reduction scenarios. These computations and scenario analyses are derived from (1) empirical relationships based on Corsica River estuary observations, (2) from comparative analyses of data from diverse estuaries, including the Corsica, and (3) from development and inspection of conceptual models that emphasize ecological feedback effects.

Empirical Analyses of Corsica River Estuary Data

One approach to estimating the water quality improvements that are expected from nutrient load management is to use phytoplankton chlorophyll-a as a master variable and develop a sequence of statistical relationships that link watershed management to estuarine water quality. These included the following: (1) a relationship between nutrient loading and chlorophyll-a (Figure 13)[44], (2) a relationship between chlorophyll-a and water column light attenuation (Figure 14), and (3) a relationship between chlorophyll-a and water column hypoxia (Figure 17). An algorithm that links these statistical models allows us to calculate potential improvements in both water clarity (and thus habitat for benthic plants) and dissolved oxygen conditions resulting from a range of reductions in nutrient (primarily N) loading. Based on our analysis of watershed BMPs, we estimated that the maximum possible reduction in N-loading to be 65% (= (projected load reduction/current load)*100). However, given uncertainties in this analysis of BMP effectiveness, we consider that a 50% reduction is probably a more achievable goal. To estimate the percent change (or "% Benefit") in bottom plant habitat, resulting from various load reductions, we (1) calculated summer chlorophyll-a for each reduced loading level (Figure 13), (2) then calculated Secchi depth at the chlorophyll-a level from (1) and Figure 14, and (3) estimated the change in the area of sediment receiving at least 1% light, based on the projected Secchi depth increases and the bathymetric data (Figure 15)[45]. Similarly, the calculated summer chlorophyll-a for each loading level (Figure 13) was entered into the equation from Figure 17 to compute the anticipated reduction in the number of summer hypoxic hours for each loading reduction value.

Estimated Water Quality Improvements

Due to the nature of the relationships and the constraints on potential load reductions, our predictions include positive (improved water quality), but relatively linear responses of the Corsica River estuarine ecosystem to reduced loading (Figure 20). Given the range of nutrient loading and chlorophyll-a observed during 2005-2008, we would expect a 50% reduction in nutrient loading (from 0.2 to 0.1 g N m^{-2} d^{-1}) to yield a 70% reduction in summer chlorophyll (from 75 to 23 mg m^{-3}). Such a reduction in chlorophyll-a would also lead to a 75% improvement in water clarity (Secchi Depth), which, because of the areal distribution of water depth for the Corsica River estuary, would lead to a nearly 95% increase in the area of Corsica river sediments that could support benthic algae (Figure 20) and 60% increase in estuarine area that would support SAV habitat (where light at the sediment surface exceeds 15% of that at the water

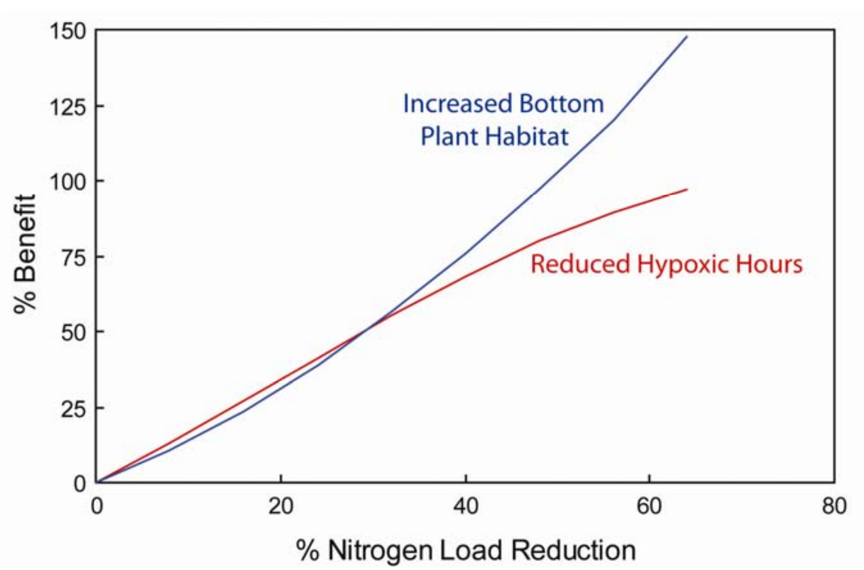

Figure 20: Potential nitrogen load reductions and simulated % changes in summer hypoxic hours and habitat for benthic algae in the Corsica river estuary. These predictions are based upon statistical relationships between nutrient loading and chlorophyll-a, and between chlorophyll-a and water clarity and hypoxia.

surface[45]). Much of this habitat, however, would be in the upper reaches of the Corsica estuary near Sycamore Point. A historical map of SAV distribution in the Corsica estuary from the summer of 1957 does not show any SAV in this region (Figure 21), probably reflecting limitation by other factors such as sediment type[45]. No such limitation is evident in more seaward regions of the estuary (Figure 21).

If we consider the historic map of SAV distribution from August 1957 to be representative of water quality conditions targeted for Corsica restoration, we can estimate the nutrient reductions needed to achieve this historic SAV distribution. In August 1957, it appears that SAV was present in the shoals of the Corsica in waters of a maximum depth of approximately 1 m. Based on Figure 15, a Secchi depth between 0.7 and 1 m, would provide the minimum light (15%) needed to support SAV growth where it was present in 1957. The proposed 50% reduction in N load, which is achievable over the next decade with ambitious participation in cover cropping, storm water and septic system upgrades throughout the watershed, would, based on this analysis, create sufficient water clarity to provide adequate light conditions needed to support historical SAV distributions.

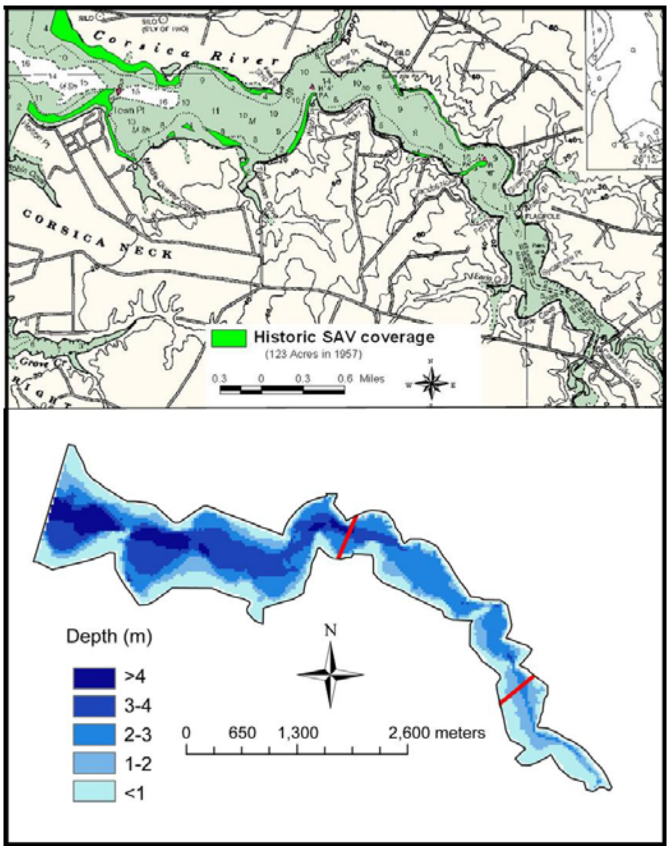

Figure 21: (top panel) Map of SAV cover in the Corsica estuary on August 6, 1957 and (bottom panel) map of Corsica River bathymetry, showing 3 general regions of depth, including the very shallow upper estuary (< 1 m), the shallow mid-estuary (1-3 m) and the deeper lower estuary (> 3 m common). Recent Arial surveys of the Corsica estuary (2006-2008) indicate no presence of SAV. SAV distribution map courtesy Mike Naylor – MD-DNR.

The same 50% reduction in N load and associated chlorophyll-a decline would also reduce the number of hypoxic hours in the estuary by 80%, essentially eliminating this water quality problem. Analyses by DNR suggest that hypoxia has probably contributed substantially to observed fish kills in the Corsica estuary. In any case, current hypoxia levels have certainly restricted important habitats for fish and benthic invertebrate species during the summer in the upper Corsica, and removal of this hypoxia would surely benefit the ecosystem.

Comparative Analyses and Feedback Loops

There are reasons to expect that the Corsica estuary's response to nutrient load reductions will not be characterized by a linear recovery trajectory. The Corsica is somewhat unique among Chesapeake Bay tributaries in its very shallow nature (mean depth ~ 1 m). In most estuaries with similar mean depths, ecosystem primary production and respiration are predominantly benthic processes, where benthic algae and/or SAV are dominant primary producers. Photosynthesis and respiration of deeper coastal ecosystems tend to be dominated by plankton. Consequently, the % of total ecosystem respiration occurring in benthic habitats tends to decrease with increasing water depth (Figure 22). In the Corsica, however, a higher than expected fraction of total respiration occured in the water column (Figure 22)[46]. This is attributable to the massive rates of water column algal production and respiration that are fueled by exceptionally high nutrient inputs and efficient nutrient recycling. Thus, in the current state of the estuary, water column respiration is much higher than expected, based on water depth. One consequence of such high water column respiration (and related photosynthesis) is that nutrient uptake and regeneration rates in the water column are quite high, which caused each unit of nutrient to be reused many times before it leaves the estuary[47].

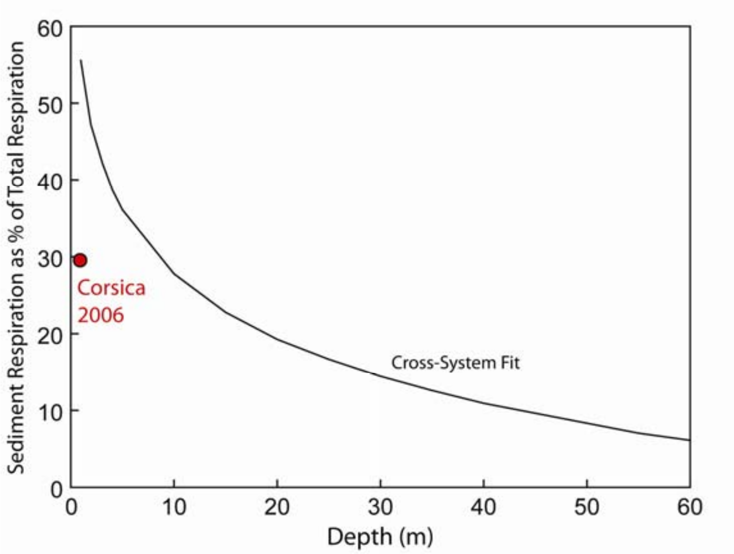

Figure 22: Relationship of spring-summer % sediment respiration (of total system respiration) to water depth from a cross-system comparison[45] (black line) with the data from the Corsica estuary in 2006 (red circle).

This aspect of the Corsica estuary, which in effect enhances eutrophication beyond what is expected from nutrient loading alone, may also serve to accelerate recovery once remediation has begun. Because the system is so shallow, a 50% reduction of nutrient loading will result in a 90% increase in bottom sediments that receive enough light to support benthic algae. Such algae serve two purposes that would likely develop a positive feedback loop that reduces eutrophication rapidly once nutrient loads begin to decline. With sufficient light reaching the sediment surface, benthic algae will absorb nutrients from the sediments (and water) and reduce nutrient levels available to support high rates of phytoplankton growth, as well as harmful algal blooms and hypoxic water conditions. Further, benthic algae form cohesive mats and SAV beds increase friction, both effectively reducing resuspension of bottom sediments, thereby further enhancing water clarity (Figure 23)[48]. For example, simple experiments were conducted using sediment cores from the Corsica River estuary, where some cores were exposed to light and others kept in the dark. Cores with sediments exposed to light had much lower nutrient release rates to the water column and also less oxygen demand than cores with the same sediments incubated in the dark (Figure 23). Thus, there is evidence that such enhanced recovery is possible, and these enhanced effects may become evident before a full 50% load reduction has been achieved. If this is the case, we would hopefully monitor and observe a more rapid recovery, which would provide promise for continued restoration.

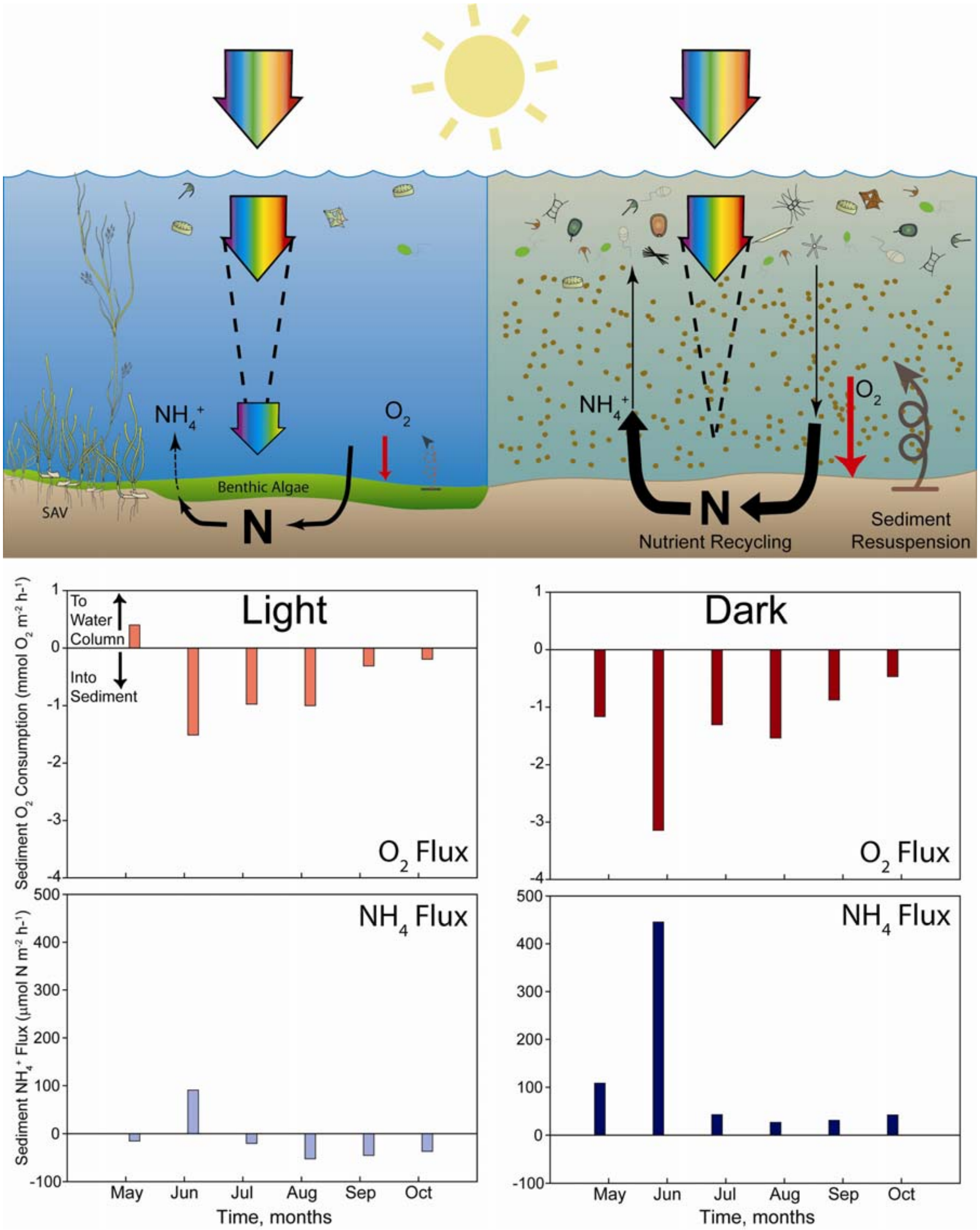

Figure 23: Conceptual diagram of water column-sediment nutrient interactions under conditions where (right) the sediments do not receive more than 1% of surface sunlight and (left) sediment receive enough sunlight to support benthic algae. In conditions where water clarity is clear enough to illuminate the sediments, benthic algal communities sequester nutrients and produce O_2 and fewer sediment nutrients are made available to water column algae. In the case where watershed nutrient loads maintain high water column algal biomass, water clarity is poor enough that light does not reach the sediment surface. Where sediments are in the dark, benthic algae cannot grow, and sediment O_2 consumption is high, as are fluxes of N and P to the water column. Measurements of sediment-water fluxes of O_2 and N support this conceptual framework, as sediments incubated in the light consume less O_2 than sediments incubated in the dark (top figures). Meanwhile, photic sediments were generally a sink for N, while dark sediments were a source of N to the water column (bottom figures). Experiments and data were performed and collected by Jeff Cornwell and Mike Owens.

LESSONS FROM THE CORSICA RIVER PROJECT

This report represents one end-point of the Corsica River monitoring and analysis program. Many measurements have been made (some continue) and a series of analyses have been completed providing quantitative assessments of current water quality and habitat status. Other analyses assessed the relative importance of nutrient sources and fates. Relationships between nutrients and critical ecosystem properties (e.g., water transparency and algal blooms, hypoxia) have also been developed. Finally, these data were combined with other observations to compute potential ecosystem responses to nutrient load reduction scenarios. Although the main objectives of the Corsica River restoration program (i.e., reducing nutrient input rates) remain to be fully completed, analyses in this report offer some encouraging conclusions indicating that realistic nutrient reduction targets will result in recovery of water quality conditions that approximate those observed in this system 50 years ago.

Having completed this aspect of the Corsica program it is appropriate to consider what has worked well and what needs to be done better as Maryland moves forward with restoration programs throughout Chesapeake Bay and its tributaries. In that context, it is important to ask what we have learned and how we could strengthen such future programs. This section makes recommendations and assessments of the science-based monitoring and research that has taken place in the Corsica River program. We are not making recommendations regarding policy issues related to restoration. We have identified three categories of issues needing consideration and these are explained below.

Criteria for Site Selection

The availability of previously collected monitoring and research data sets for a potential restoration site is an important consideration for a variety of reasons. Obviously, there are cost savings if important data are already available. In addition, the degree of nutrient induced impact can, in part, be estimated using statistical models derived from these data, thus allowing quantitative assessment of restoration needs. In some cases it may also be possible to implement, using available data, a simple box model to assess potential influences of downstream tidal areas on the targeted restoration site. One of the basic features of temperate estuaries is variability on multiple temporal scales including tidal, daily, seasonal and inter-annual. Available data can be used to assess the scales of variability in a targeted system, which is needed to design future monitoring programs.

There were also a number of additional criteria used in selecting targeted watershed restoration sites, as was the case for the Corsica, and this procedure should be used in the future. One key element of the site selection process involved the anticipated degree of local participation in terms of educational, planning and financial resources devoted to restoration. While a strong case was made for these criteria in selecting the Corsica watershed as a restoration site, there has not been much progress in the areas of aggressive cover cropping of agricultural lands, storm water management or installation of denitrifying septic systems. The point source program has been completely successful but progress in other areas has been slow. A remaining question is, are there ways to ensure more comprehensive and effective participation in small watershed restoration projects?

Critical Measurements and Activities

There are several lessons learned concerning critical measurements needed for solid analysis of estuaries undergoing restoration activities and assessments. We note the following as being especially important.

- Establish early in the program the direct measurements of nutrient and other material inputs to the targeted estuary. In general this means establishing gauging stations on major streams entering the estuary used to estimate water inputs and nutrient loads. These sites also need to be maintained for long periods of time (~years to decades), especially in areas where groundwater flows constitute a large fraction of stream inputs. In brief, a measurement program needs to be established so that nutrient and other inputs to the system are accurately estimated before, during, and after restoration activities. Without such measurements the effectiveness of management actions can not be adequately assessed, little is learned, and there is limited carry-over to the next restoration project.
- Time series measurements of key variables are essential for assessment and scientific understanding. Estuaries are inherently variable and, because of this, measurements of key variables need to be conducted over substantial periods of time (multiple years) to characterize water quality and habitat conditions, as well as estuarine responses to management activities. In the case of the Corsica River estuary, multiple years of CONMON data collected at distinctive sites along the estuarine salinity gradient were particularly useful.
- In the Corsica River program several important nutrient processes (e.g., denitrification and nutrient burial) were measured and, as it turns out, were key to understanding eutrophication effects and potential responses to nutrient load reductions. We strongly encourage including selected process measurements to complement routine monitoring and data collection. Field experiments also yield important information concerning estuarine responses to management action.
- In a number of cases, water quality measurements were made only during the warmer seasons (April-October). Our analysis of the Corsica suffered because of this, and we were forced to make some extrapolations to obtain results on an annual basis. For example, freshwater and nutrient inputs tend to be highest during late-winter and spring, while nutrient-induced effects are most severe in late spring through early fall. To accurately capture this coupling of input and response, key variables and processes need to be measured throughout the year.
- During our analysis of the Corsica River data set, we found that it would have been useful to have data from a local weather station recording solar radiation, temperature, wind direction and speed, and precipitation. Such a site would provide more accurate data at the site level and would give us a better understanding of effects from storm events.
- Finally, estuarine restoration requires a multi-year effort. To be done well, data collection should be initiated prior to the on-set of restoration activities and continued during and after restoration activities. This report, which assembled and synthesized a large amount of data, also took much longer to complete than anticipated, partly because integrative scientific analyses of data in support of restoration activities (e.g., this report) requires time-series data over extended periods and a range of time-space scales.

Cross-System Comparisons

The Corsica River restoration program was the first of its kind in this region, and there were ample opportunities for learning experiences. It is expected that there will be many more restoration programs sited on estuaries both large (e.g., Patuxent) and small (e.g., Corsica) in the future and lessons learned in the Corsica, as well as data generated in this system, can be effectively used in other restoration projects.

An approach we effectively used in the Corsica River analysis was one ecologists call *cross-system comparisons*. This approach uses data from similar systems, along with data from the site under study to increase the number of observations and to increase the generality of results. For example, we only had 2 years of nutrient loading data for the Corsica (both N and P). It's reasonable to ask how these rates compare to those in other estuarine systems. Are the Corsica N and P loads high or low compared with other systems? We developed a comparative load graph using data from approximately 36 other estuarine systems and added the Corsica data to this analysis and quickly saw that loads to the Corsica were intermediate between systems with low and very high loading rates. In another comparative analysis we found that the N load versus N concentration relationship in the Corsica was the same as it is for other small and large tributaries of Chesapeake Bay. Finally, and most importantly, we attempted to establish a relationship between nutrient loading rates and algal biomass in the Corsica. However, we did not have enough data from the Corsica to develop such a relationship. We therefore examined the literature and the long-term Maryland tributary water quality data for other sites and then had a sufficient number of observations for developing a useful relationship between these two key variables. As time goes, on data will be available from restoration sites in addition to the Corsica and these data can be effectively used in cross-system comparisons for management purposes. Additional data are needed to confirm that key relationships (e.g., phytoplankton chlorophyll-a versus nitrogen loading) derived from cross-system comparisons also hold over time for specific systems like the Corsica, where there are temporal changes in the independent variable (e.g., nutrient loading).

REPORT APPENDIX

The purpose of this appendix is to provide details concerning important items in this report. Included are appropriate scientific references supporting statements and conclusions made in the report, some details regarding calculations presented in this report, and links to Corsica River technical reports that serve as the basis for much of the work presented here. The appendix is organized by major headings of the report.

INTRODUCTION

The following are papers and reports supporting issues referred to in the Introduction. Additional sources are contained in these reports:

[1]Nixon, S.W. 1998. Enriching the sea to death. Scientific American 9(3):48-53

[2]National Research Council. 2000. Clean coastal waters: understanding and reducing the effects of nutrient pollution. National Academy Press, Washington, D.C.

[3]Cloern, J.E. 2001. Our evolving conceptual model of the coastal eutrophication problem. Marine Ecology Progress Series 211: 223-253

[4]Diaz, R.J. 2001. Overview of hypoxia around the world. Journal of Environmental Quality 30: 275-281

[5]Diaz, R.J. and R.R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. Science 321: 926-929

[6]Kemp, W.M., W.R. Boynton, J.E. Adolf, D.F. Boesch, W.C. Boicourt, G. Brush, J.C. Cornwell, T.R. Fisher, P.M. Glibert, J.D. Hagy, L.W. Harding, E.D. Houde, andD.G. Kimmel, W.D.M., R.I.E. Newell, M.R. Roman, E.M. Smith, and J.C. Stevenson. 2005. Eutrophication of Chesapeake Bay: historical trends and ecological interactions. Marine Ecology Progress Series 303: 1-29

[7]Hassett, B., M. Palmer, E. Bernhardt, S. Smith, J. Carr, and D. Hart. 2005. Restoring watersheds project by project: trends in Chesapeake Bay tributary restoration. Frontiers in Ecology and the Environment. 3: 259-267.

[8]Maryland's Clean Water Action Plan Report 12/31/98:
http://www.dnr.state.md.us/cwap/

[9]Primrose, N.L., J. Jaber, and I. Spotts. 2008. The Synoptic Survey – Benefits of Being Everywhere at Once. 16th National Nonpoint Source Monitoring Workshop, Columbus, Ohio. http://streams.osu.edu/NPSPapers/Primrose_Paper.pdf

CONCEPTUAL MODELS OF THE CORSICA RIVER ESTUARY

The following items were used in developing this portion of the report:

[10]IAN Conceptual Diagram Image Library http://ian.umces.edu/symbols/

[11]Thresholds in the Recovery of Eutrophic Coastal Ecosystems: A Workshop Report
W.M. Kemp and E.B. Goldman, Editors
http://www.mdsg.umd.edu/store/reports/thresholds/

CORCICA LAND-WATER CONNECTIONS

[12]Corsica River Watershed Land Use Map (Figure 2) is Map 6 from the Corsica River Watershed Characterization (October 2003):
http://dnrweb.dnr.state.md.us/download/bays/cr_char.pdf

[13]High frequency (15 minute) dissolved oxygen, temperature, chlorophyll-a, and salinity data were collected by sensors maintained by the Maryland Department of Natural Resources as part of the Eyes on the Bay Program at 4 sites for varying durations from 2003 to the present. The program is known as CONMON (CONtinuous MONitoring). (http://mddnr.chesapeakebay.net/newmontech/contmon/eotb_results_corsica.cfm).
At two stations (Possum Point and The Sill), water quality parameters are collected near the surface and near the bottom, while samples are collected near the bottom at Sycamore Point, which is a well-mixed water column. These

[14]Corsica River Watershed Monitoring Station Map (Figure 4) is based on the 2000 Maryland Department of the Environment TMDL Final Report for the Corsica River estuary
http://www.mde.state.md.us/assets/document/tmdl/corsica/corsica_tmdl_fin.PDF

[15]Secchi Depth and nutrient concentration data were collected monthly during cruises for DATAFLOW (http://www.gonzo.cbl.umces.edu/NewFiles/DF%20Description.pdf) at several stations. DATAFLOW collects water quality data instantaneously over large areas for high resolution spatial maps of water quality data.

[16]SONE (Sediment-Water Oxygen and Nutrient Exchanges) is a method for quantifying the exchange of dissolved oxygen and inorganic nutrients between estuarine sediments and the overlying water column. These measurements were made along the axis of the Corsica estuary during the spring, summer, and fall of 2006. See http://www.gonzo.cbl.umces.edu/waterquality.html Interpretive Report No 24 (September, 2007) for information and data concerning SONE measurements.

NUTRIENT SOURCES

[17]Three stream gauges are currently maintained by the United States Geological Survey (USGS) and the Maryland Department of Natural Resources (MD-NDR) at Mill Stream, Gravel Run, and Three Bridges Branch. Nutrient samplers, operated by the Maryland Department of the Environment (MDE), collect water samples at consistent intervals and mix them into a single sample that is collected once a week and analyzed for particulate and inorganic nitrogen and phosphorus. Stream flow data from Three Bridges Branch are available at http://waterdata.usgs.gov/nwis/uv?01494150. Not all of the watershed stream flow was gauged. Diffuse source loads from non-gauged portions of the watershed were estimated by computing areal loads (e.g., pounds/acre/year) from a gauged watershed in the Corsica basin having similar land uses and applying that rate to the land in un-gauged portions of the watershed.

[18]Nutrient loads from with stormwater runoff associated with the town of Centerville were estimated by assuming that the yield of nutrient per unit watershed area was the same in Centreville as in the Gravel Run watershed. This is a conservative estimate and it is necessary because much of the land made up by Centreville is non gauged by stream flow and nutrient monitors. The estimate assumes that all loads coming from the fraction of the Corsica watershed comprised by Centreville are stormwater flows, that is, that they flow over land directly into streams.

[19]Atmospheric wet deposition (rainfall) of nitrogen was based on analyses from the National Atmospheric Deposition Program site at Wye, Maryland. This category of nitrogen input includes just the nitrogen in rainfall falling directly on the surface waters of the Corsica River estuary. Nitrogen in rainfall landing in the basin is captured in the diffuse and stormwater terms. Wet fall nitrogen data can be obtained from http://nadp.sws.uiuc.edu/ We did not include estimates of dry fall atmospheric deposition. Some researchers have estimated that total atmospheric nitrogen deposition is almost twice the wet fall deposition used in this evaluation; thus, our estimates are almost certainly low. Phosphorus deposition in rainfall is very small and was not estimated.

[20]Point source (e.g., sewage treatment plant discharges) data were from the Maryland Department of Environment http://www.mde.state.md.us/. A major reduction in discharge volume and nutrient concentrations in discharges occurred in 2005 when the Centerville plant was upgraded to Enhanced Nutrient Removal (ENR) status and most of the annual discharge diverted to a large holding pond and then used for spray irrigation of agricultural crops.

[21]Net exchanges of nitrogen and phosphorus between the Corsica and Chester Rivers were computed by a salt-and water-balance computation coupled to nutrient distributions in the Corsica River estuary. This computation also computed exchanges between different regions of the Corsica estuary. Details of the computations and results can be found in Chapter 4.0 of this report: http://www.gonzo.cbl.umces.edu/Level1Report25.pdf

[22]The below figure (Figure A) includes monthly estimates of nutrient loading from diffuse loads (streamflow), wastewater treatment plants (WWTP), and atmospheric deposition for 2006. Loads are generally higher during spring, but the anomalously high June-July precipitation in 2006 cause elevated loads during that period as well. The second figure (Figure B) indicates a time series of monthly streamflow for the Tuckahoe River (which is adjacent to the Corsica), including means for Spring, Summer, and the entire year. This time series displays how the stream flow of the Tuckahoe is highly correlated to flow in two Corsica River tributaries (Three Bridges Branch and Gravel run) and also how summer nutrient loads were generally low in summer, except for 2006.

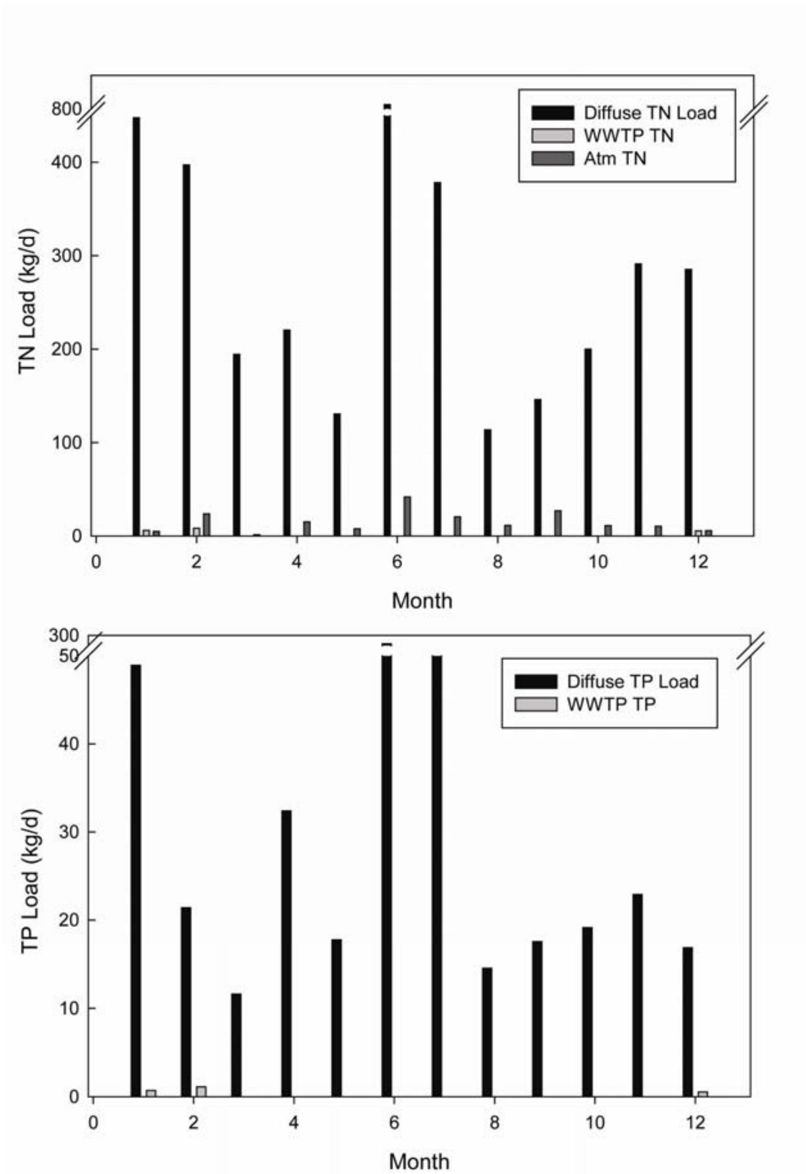

Figure A: Monthly estimates of nutrient loading from diffuse loads (streamflow), wastewater treatment plants (WWTP), and atmospheric deposition for TN and TP during 2006. Atmospheric deposition of TP is assumed to be zero.

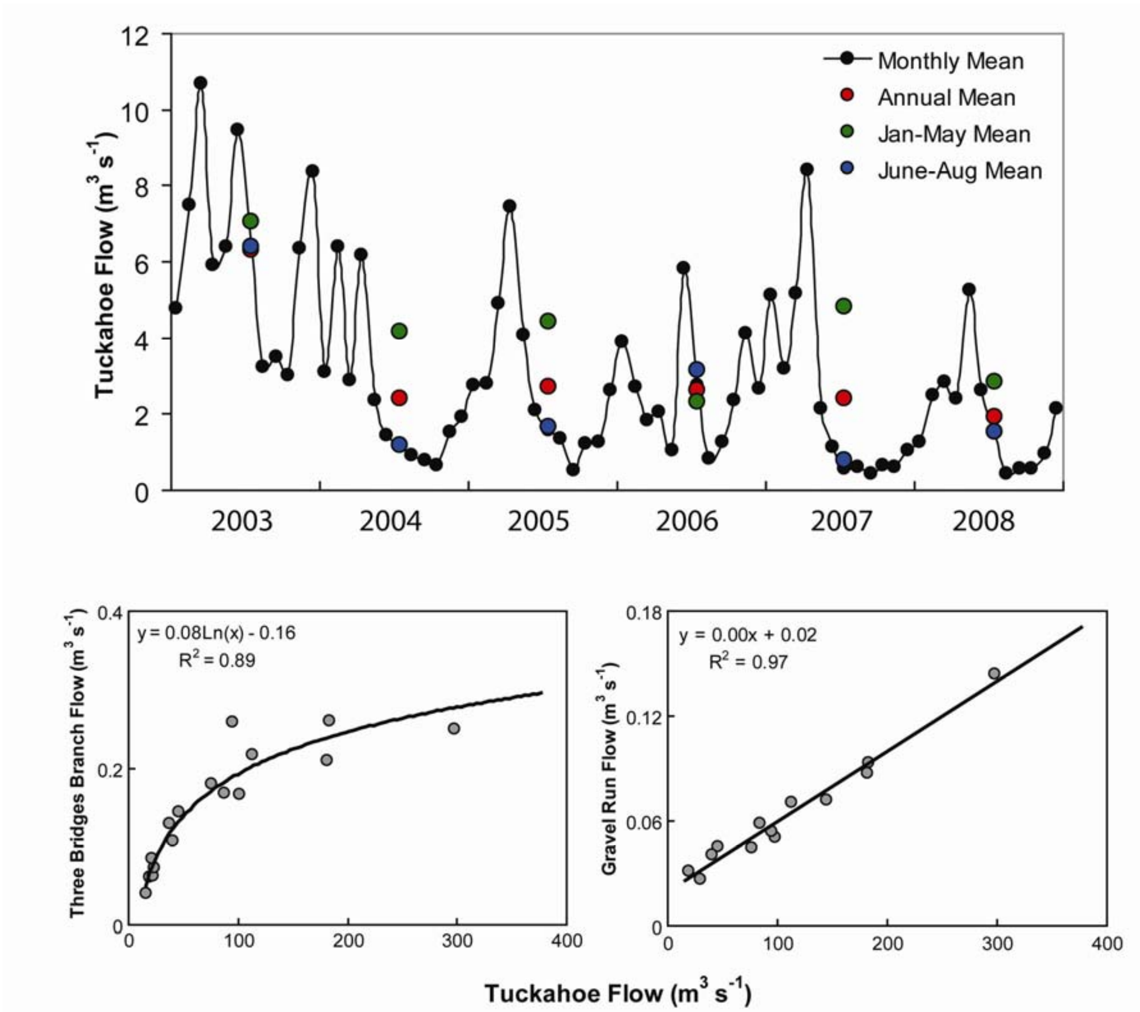

Figure B: (top panel) Time series (2003-2008) of monthly streamflow for the Tuckahoe River , including means for Spring (January to May), Summer (June to August), and the entire year. (bottom panel) Correlations between streamflow in the Tuckahoe River with that in Three Bridges Branch (left) and Gravel run (right) for available data in 2006-2007.

[23]Data in Figure 9 are from Boynton, W.R. and Kemp, W.M., 2008. Estuaries, pp. 809-856. In: Capone, D.G., Bronk, D.A., Mulholland, M.R., and Carpenter, E.J. (Eds.), *Nitrogen in the Marine Environment 2nd Edition*. Elsevier Inc., Burlington, Massachusetts.

[24]Data in Figure 10 are from W.R. and Kemp, W.M., 2008. Estuaries, pp. 809-856. In: Capone, D.G., Bronk, D.A., Mulholland, M.R., and Carpenter, E.J. (Eds.), *Nitrogen in the Marine Environment 2nd Edition*. Elsevier Inc., Burlington, Massachusetts.

[25]For a broader study of nutrient limitation in the Chesapeake Bay ecosystem, see: Fisher, T.R., E.R. Peele, J.W. Ammerman, and L.W. Harding, Jr. 1992. Nutrient limitation of phytoplankton in Chesapeake Bay. Marine Ecology Progress Series 82: 51-63

NUTRIENT FATES

[26]Basic and more advanced information concerning denitrification can be found in Capone, D.G., Bronk, D.A., Mulholland, M.R., and Carpenter, E.J. (Eds.), *Nitrogen in the Marine Environment 2nd Edition*. Elsevier Inc., Burlington, Massachusetts.

[27]Denitrification measurements were made in the Corsica River estuary and in one of the stream/marsh areas at the head of the estuary. Station locations, measurement techniques and all data were reported in:

Cornwell, J. C., M. Owens and C. Palinkas. 2007. Denitrification and nutrient balance in the Corsica River sediments, Maryland, pp.85-102. In W. R. Boynton et. al. 2007. Targeted watershed Measurement Program and Key Process Evaluation. Year 1: Corsica River Estuary Data Report Tech Rept Series No. TS-531-07-CBL of the University of Maryland Center for Environmental Science.

[28]Nitrogen burial rates were estimated from a variety of sites in the Corsica River estuary and in the stream/marsh areas at the head of the estuary. Station locations, measurement techniques and all data were reported in:

Cornwell, J. C., M. Owens and C. Palinkas. 2007. Denitrification and nutrient balance in the Corsica River sediments, Maryland, pp.85-102. In W. R. Boynton et. al. 2007. Targeted watershed Measurement Program and Key Process Evaluation. Year 1: Corsica River Estuary Data Report Tech Rept Series No. TS-531-07-CBL of the University of Maryland Center for Environmental Science.

[29]Data provided in Table 4 were from:

W.R. and Kemp, W.M., 2008. Estuaries, pp. 809-856. In: Capone, D.G., Bronk, D.A., Mulholland, M.R., and Carpenter, E.J. (Eds.), *Nitrogen in the Marine Environment 2nd Edition*. Elsevier Inc., Burlington, Massachusetts.

[30]Transport of water and materials within sectors of the Corsica River estuary and between the Corsica and the Chester River estuary were estimated using a box-model approach. Details of this procedure and results were reported in:

W. M. Kemp, M. T. Brooks, and J. M. Testa. 2007.Box-Modeling Analysis of the Corsica River Estuarine System. In: W. R. Boynton et. al. 2007. Targeted watershed Measurement Program and Key Process Evaluation. Year 1: Corsica River Estuary Data Report Tech Rept Series No. TS-531-07-CBL of the University of Maryland Center for Environmental Science.

INCREASED N INPUTS CAUSE MORE ALGAE IN THE ESTUARY

[31]The data in Figure 12 were collected monthly during cruises of the DATAFLOW Program (http://www.gonzo.cbl.umces.edu/NewFiles/DF%20Description.pdf. The DATAFLOW approach collects water quality data rapidly over large spatial areas (surface waters of the full estuary are measured in 3-4 hours) allowing for development of high resolution spatial maps. The site for maps of temperature, dissolved O_2, salinity, and chlorophyll-a in the Corsica: http://mddnr.chesapeakebay.net/sim/dataflow_data.cfm

[32]Data used in constructing Figure 13 were obtained from multiple sources. Chlorophyll-a data from the Corsica, Back, Sassafras, and Elk Rivers were obtained from the Maryland Department of Natural Resources via the Chesapeake Information Management System (CIMS, http://www.chesapeakebay.net/data_waterquality.aspx) and averaged over depths of 0.5 to 3 m from May to August. TN Loading data from the Back, Elk, and Sassafras Rivers were obtained from the Chesapeake Bay Watershed Model. Loading data from the Corsica River estuary were either monitored by the USGS or computed: http://www.gonzo.cbl.umces.edu/Level1Report25.pdf. Data for the Coastal Bays were taken from: Boynton, W.R., Hagy, J.D., L. Murray, C. Stokes, and W.M. Kemp 1996 A comparative analysis of eutrophication patterns in a temperate coastal lagoon. Estuaries 19: 408-421.

INCREASED ALGAE CONTRIBUTES TO DECREASED WATER CLARITY

[33]A Secchi disk is an easy way to measure the amount of light in the water column. The disk, though useful, does not measure scattering of light upwards by particles in the water column. For more information, visit: http://www.mlswa.org/secchi.htm

[34]Details of the calculations and analyses to determine the causes of light attenuation in the Corsica river estuary can be found in Chapter 5.0 of the following report: http://www.gonzo.cbl.umces.edu/Level1Report25.pdf

INCREASED ALGAE CAUSES LESS DISSOLVED OXYGEN

[35]In the Corsica River estuary dissolved oxygen generally drops to levels that fish avoid during night hours during late spring, summer and early fall. An oxygen level of 2 milligrams per liter is considered hypoxic, although levels of 5 mg/l will also cause some fish avoidance. (see http://www.esa.org/education_diversity/pdfDocs/hypoxia.pdf).

[36]In Figure 16, daily hours of hypoxia were computed by summing the 15-minute periods that contained dissolved oxygen concentrations below 2 milligrams per liter at each CONMON station in the estuary.

[37]Some useful references on hypoxia, its causes, and its response to remediation efforts:

Conley, D.J., Carstensen, J., Vaquer, R. and Duarte, C.M. 2009. Ecosystem thresholds with hypoxia. Hydrobiologia. 629: 21-29.

Diaz, R.J. and Rosenberg, R. 1995. Marine benthic hypoxia: A review of its ecological effects and the behavioral responses of benthic macrofauna. Oceanography and Marine Biology. 33: 245–303.

Kemp, W.M., Testa, J.M., Conley, D.J., Gilbert, D. and Hagy, J.D. 2009. Coastal hypoxia responses to remediation. Biogeosciences Discussions. 6: 6889-6948. http://www.biogeosciences-discuss.net/6/6889/2009/bgd-6-6889-2009.pdf

Mee, L. 2006. Reviving dead zones. Scientific American. 295: 78-85.

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

Rabalais, N.N., Turner, R.E., and Wiseman, W.J. 2002. Gulf of Mexico hypoxia, A.K.A. "The Dead Zone". Annual Review of Ecology and Systematics. 33: 235-263.

Tyler, R.M., Brady, D.C., and Targett, T. 2009. Temporal and spatial dynamics of diel-cycling hypoxia in estuarine tributaries. Estuaries and Coasts. 32: 123-145.

NUTRIENT MANAGEMENT SCENARIOS

[38]Comments contained here refer to Table 5 in the Report summarizing potential and actual nitrogen load reductions to the Corsica River estuary. The large (12800 kg N/yr) sewage treatment plant input was from the period prior to sewage treatment plant upgrade to ENR coupled to wastewater lagoon system operation. The current point source N loads (2000 kg N/yr) to the Corsica River estuary mainly occur during winter periods when the lagoon is filled and spray irrigation of effluent on agricultural fields not possible. No further reductions are anticipated from point sources.

[39]No immediate change is expected in atmospheric deposition of N to the surface waters of the Corsica River estuary or basin. Any significant reductions would likely come from regional to national-scale reductions in N-emissions from power plants and automotive exhausts. There have been small decreases in NOx deposition during the last decade. In table 5 there is no expected N-load reduction due to atmospheric deposition.

[40]Septic systems were divided into two categories: 1) those adjacent to tidal waters (161 systems) where leachate would drain directly to the estuary and 2) those in the basin (648) where leachate would flow into streams draining into the Corsica River estuary. With current septic system denitrifying technology an N removal rate of 75% was used because this was intermediate between the least and most efficient N systems.

[41]Reductions in storm water loads were estimated by examining the various storm water management devises evaluated under field conditions by the University of New Hampshire's Storm Water Center (http://www.unh.edu/erg/cstev). Bio-retention systems, gravel wetlands, retention ponds and various swale systems indicated removal efficiencies of about 50%. Estimated storm water N loads were reduced by 50% in this evaluation.

[42]Diffuse sources include groundwater N loads from the Corsica basin but exclude stormwater flows from the town of Centerville. The diffuse source value (87300 kg/yr) is 9700 kg/yr less than the value shown in Table 1 and Figure 11 because non-tidal water septic loads were removed and counted separately in this evaluation. The TN load from cropland was estimated by computing the average annual base flow stream TN concentration (4.5 mg/l TN), multiplying this by the volume of water recharging the

groundwater system (~0.3 m3/m2/year) and then dividing this value by the estimated area of cropland (5464 ha). This yield was then reduced by applying a cover crop efficiency coefficient (53% for early drilled rye; 23% for late drilled rye) developed by the Cover Crop Panel and MAWP and then multiplying this reduced load per area by the area of agricultural cropland. The practical cover crop heading assumed that 33% of cropland could be planted early, 33% could be planted late and 33% would not be available for any cover crops. The maximum cover crop scenario assumed that all cropland could be planted early. Current N load reductions due to current cover cropping used an area of 526 ha and a 53% reduction coefficient.

[43]Data in Figure 18 were from inspection of the three stream gauges currently maintained by the United States Geological Survey (USGS) and the Maryland Department of Natural Resources (MD-DNR) at Mill Stream, Gravel Run, and Three Bridges Branch. Nutrient samplers, operated by the Maryland Department of the Environment (MDE), collect water samples at consistent intervals and mix them into a single sample that is collected once a week and analyzed for particulate and inorganic nitrogen and phosphorus. Stream flow data from the stream known as Three Bridges Branch are available at http://waterdata.usgs.gov/nwis/uv?01494150 Based on visual inspection, flow records were separated into base flow and storm flow components. Base and storm flow loads were then calculated using TN concentrations measured during appropriate base and storm flow periods of time.

LIKELY ECOSYSTEM RESPONSES TO NUTRIENT LOAD REDUCTIONS

[44]For more information and examples of comparative ecological approaches see:

Boynton, W. R. and W. M. Kemp. 2000. Influence of river flow and nutrient loads on selected ecosystem processes: A synthesis of Chesapeake Bay data, p. 269-298. In: J. E. Hobbie (ed.) Estuarine Science: A Synthetic Approach to Research and Practice. Island Press, Washington, DC.

Vollenweider, R. A. 1976. Advances in defining critical loading levels of phosphorus in lake eutrophication. Memorie-Istituto Italiano de Idrobiologia 33: 53-83.
The 1957 SAV map for the Corsica River estuary was provided by Dr. Michael Naylor, MD-DNR, Tawes State Office Building, Annapolis, MD

[45]The depth contour map (Figure 20) was based on National Ocean Service Hydrographic Survey Data obtained from the NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html) data sets and developed by M. Brooks, Horn Point Environmental Laboratory, Cambridge, MD

A useful report on the factors limiting SAV growth is below:

Kemp, W. M., R. Batiuk, R. Bartleson, P. Bergstrom, V. Carter, G. Gallegos, W. Hunley, L. Karrh, E. Koch, J. Landwehr, K. Moore, L. Murray, M. Naylor, N. Rybicki, J. C. Stevenson, D. Wilcox**.** 2004. Habitat requirements for submerged aquatic vegetation in Chesapeake Bay: Water quality, light regime, and physical-chemical factors. Estuaries 27: 363-377.

[46]The data used to develop the cross-system fit for the fraction of total respiration as a function of depth was originally developed and then expanded in the following publications:

Kemp, W.M. and W.R. Boynton. 1992. Benthic-pelagic interactions: Nutrients and oxygen dynamics, p. 149-209. In: D.E. Smith, M. Leffler and G. Mackiernan. Oxygen Dynamics in the Chesapeake Bay-A Synthesis of Recent Results. A Maryland Sea Grant Book, College Park, MD

Kemp, W. M., P. A. Sampou, J. Garber, J. Tuttle, and W. R. Boynton. 1992. Seasonal depletion of oxygen from bottom waters of Chesapeake Bay: Relative roles of benthic and planktonic respiration and physical exchange processes. Mar. Ecol. Prog. Ser. 85: 137-152.

Boynton, W.R. and E.M. Bailey. 2008. Sediment Oxygen and Nutrient Exchange Measurements from Chesapeake Bay, Tributary Rivers and Maryland Coastal Bays: Development of a Comprehensive Database and Analysis of Factors Controlling Patterns and Magnitude of Sediment-Water Exchanges. Final report to Maryland Department of the Environment, Science Services Administration, TMDL Technical Development Program, Baltimore, MD. Ref. No. *[UMCES]CBL08-019. [UMCES Technical Series No. TS-542-08]*. http://www.gonzo.cbl.umces.edu/FluxSynthesisFinalReportJuly2008.pdf

[47]One of the attractive features of this approach is the simplicity of relating key management issues (nutrient load reduction) to important ecosystem responses (algal blooming, water clarity and dissolved oxygen conditions). These interactions are, however, more complex than what is implied by the statistical relationships. To provide some perspective on the multiple processes occurring in this estuary we have summarized seasonal-scale nutrient processes for the upper portion of the Corsica River estuary during 2006 (Figure 1). In each panel (representing a different season) external inputs of nitrogen are indicated on the left. Nitrogen associated with sediment re-mineralization processes is shown entering the bottom of each box. Water column processes of nutrient uptake by phytoplankton and nitrogen re-cycling by the full plankton community (phytoplankton, zooplankton, bacteria and other small protists) are shown with separate arrows within the boxes.

Several important points immediately emerge from this summary diagram. First, the sum of re-cycle processes was always much larger than the inputs of nitrogen from external sources indicating that this essential compound is used again and again during an annual period. It is likely that because of relatively long water residence times and very shallow water depths, the Corsica is particularly sensitive to nutrient additions from the landscape. Second, during summer and fall, the total supply of N (external inputs plus water column and sediment re-cycling) was equal to or substantially exceeded the amount of N used by the phytoplankton community.

Box modeling of DIN in this system indicated substantial transport of TN to the Chester River, consistent with the finding here of N being generated in excess of that used by the phytoplankton community. Finally, the N cycling rates are large. If some system feature were to change (e.g., improvement in water clarity) and the change impacted one or more N cycling processes then system dynamics might well change abruptly rather than gradually as suggested by the simple relationships referred to earlier in this report. Some evidence of non-linear behavior was observed when sediment processes were measured under light versus dark conditions, simulating a water column with better water clarity.

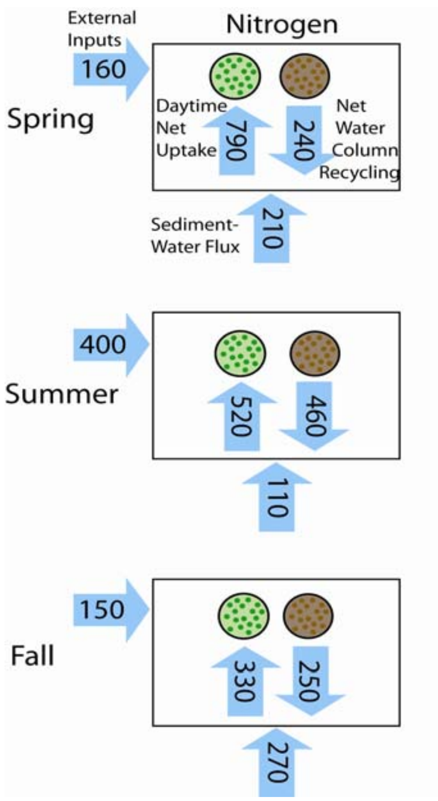

Figure 1: Seasonal fluxes of TN from external sources (watershed + atmosphere), estuarine sediments, and uptake and regeneration associated with estuarine plankton communities. Data were collected during 2006 for three periods (Spring = April + May; Summer = June + July + August; Fall = September + October). Note that N cycling rates (water column + sediment re-cycle) is greater or much greater than external inputs suggesting that a small amount of nitrogen goes a long ways because it is used and re-used many times before exiting the system. During most seasons, the total supply of N (new inputs plus recycled nutrients) equaled or actually exceeded plankton demand, even in this eutrophic estuary. Water column uptake and recycling rates were computed by multiplying the Redfield plankton nutrient ratio (O_2:N:P = 106:16:1) by rates of daytime net photosynthesis and daily net O^2 uptake (respiration), which were computed from hourly changes in O_2 concentrations recorded by CONMON sensors.

[48]Data used in Figure 24 are from:

Cornwell, J. C., M. Owens and C. Palinkas. 2007. Denitrification and nutrient balance in the Corsica River sediments, Maryland, pp.85-102. In W. R. Boynton et. al. 2007. Targeted watershed Measurement Program and Key Process Evaluation. Year 1: Corsica River Estuary Data Report Tech Rept Series No. TS-531-07-CBL of the University of Maryland Center for Environmental Science.

GLOSSARY

ALGAE: a large and diverse group of simple, *photosynthetic* organisms, who may exist as single-celled or multi-celled forms. The largest and most complex marine forms are called macroalage, while microscopic forms may be referred to as microalgae.

BENTHIC: the ecological region at the bottom of an ocean, estuary, river, or lake. Benthic generally includes the sediment surface and some layers of the sediment just below the surface. Benthic may include structures animals build on the sediment, including oyster reefs.

BEST MANAGEMENT PRACTICES (BMPS): a suite of agricultural or forestry practices that accomplish the best possible management of the land to keep its quality high for the future. In agriculture, such practices include *cover crops*, *stream forest buffers*, and *no-till field management*.

BOX MODEL: a simple model to compute the flows of water in an estuary based on balancing the volume of water and mass of salt in the estuary. Data requirements include knowing the amount of freshwater entering the estuary and the amount of salt contained within the estuary. Such flows can then be multiplied by nutrient concentrations to compute nutrients loads and transports within the estuary.

CHLOROPHYLL-A: a green pigment found in most plants and algae. Chlorophyll absorbs light most strongly in the blue and red but poorly in the green portions of the light spectrum, which gives plants their characteristic green color.

DENITRIFICATION: a process accomplished by bacteria that converts nitrate (NO_3^-) into nitrogen gas (N_2). This is one of only a few natural processes that permanently remove nitrogen from a water body.

DIATOM: a variety of phytoplankton, which are encased in a shell made of silica. Diatoms can live suspended in the water or on the sediment surface, but their encasings often cause them to sink. *See Phytoplankton.*

DIN (DISSOLVED INORGANIC NITROGEN): the sum of the concentrations of all non-carbon containing nitrogen compounds in a water body. DIN is commonly made up of nitrate (NO_3^-), ammonium (NH_4^+), and nitrite (NO_2^-).

DIFFUSE NUTRIENT INPUTS: the nutrient inputs that enter a water body at unspecified times and places, that is, inputs that c*annot* be controlled at a specific point and time (like a pipe). *See Point Nutrient Inputs.*

DIP (DISSOLVED INORGANIC PHOSPHORUS): the sum of the concentrations of all non-carbon containing phosphorus compounds in a water body. DIP is commonly made up of only *phosphate* (PO_4^{3-}).

EUTROPHICATION: is an increase in the amount of carbon loading to an ecosystem. This carbon loading may be done directly or indirectly via the enhanced production of phytoplankton organic matter with increased additions of chemical nutrients to an ecosystem.

HYPOXIA: the condition of very low oxygen concentrations. A water body is commonly considered to be hypoxic when oxygen levels fall below 2 milligrams per liter.

MORPHOLOGY: a description of the structure of the bottom of a water body, including the depth, length, and area of the water body and its various regions.

N:P RATIO: the ratio of nitrogen to phosphorus in an ecosystem. *See Redfield ratio*.

NO-TILL AGRICULTURE: occasionally referred to as zero tillage, no-till agriculture is a way of growing crops each year without disturbing the soil through tillage. No-till is an emergent agricultural technique which can increase the amount of water in the soil and decrease erosion.

PALUSTRINE: a type of wetland that is not tidal. Most freshwater wetlands are palustrine, except tidal freshwater marshes that occur in the upper reaches of many Chesapeake Bay tributaries.

PAR: Photosynthetically Available Radiation, which is one measure of the amount of sunlight reaching a water body.

PELAGIC: the ecological region of an ocean, estuary, river, or lake that is open water, or the water column. Pelagic generally includes the entire ecosystem that **is not** in the vicinity of bottom sediments.

PHOTOSYNTHESIS: is a process accomplished by all plants that converts carbon dioxide and water into organic compounds, especially sugars, using the energy from sunlight. Photosynthesis produces most all of the carbon available to feed higher organisms.

PHYTOPLANKTON: microscopic plants, which are often single-celled, who accomplish most of the photosynthesis in an ecosystem where SAV are absent or in low numbers. When present in high enough numbers, they may appear as a green discoloration of the water due to the presence of *chlorophyll* within their cells.

POINT NUTRIENT SOURCES: the nutrient inputs that enter a water body at specified times and places; that is, inputs that *can be* controlled at a specific point and time (like a pipe). Sewage treatment plants are the most common form of point nutrient sources. *See Diffuse Nutrient Inputs.*

PRIMARY PRODUCTION: the amount of carbon produced per unit time by *photosynthesis* within an ecosystem, or a community.

REDFIELD RATIO: the common ratio of nitrogen:phosphorus in *phytoplankton* (molar = 16:1). First described by Albert Redfield. When the ratio of the concentrations of N and P in a natural water body deviate from this ratio, there is limitation of *phytoplankton* growth by either N or P is possible.
REMINERALIZED: when nutrients that are incorporated into organic material are released as simpler forms (ammonium or nitrate) following the breakdown of organic material by bacteria.

RESPIRATION: a set of metabolic reactions that obtain energy from sugars, amino acids, fatty acids, etc. This process normally requires oxygen and includes the breakdown of organic matter by bacteria in aquatic ecosystems.

RIPARIAN: the interface between a river or stream and the surrounding land. Riparian zones often include the land outside the normal river bed covered by the average flood waters from the river.

SECCHI DISK: a circular metal disk painted white and black and lowered into the water to a depth where the disk disappears from sight. The depth at which the disk disappears from sight is an index of water clarity.

SEDIMENTATION: the deposition of organic material and soil particles to the sediments. Often expressed as a rate of sedimentation per unit area.

SEPTIC LEACHATE: water and associated nutrients (nitrogen and phosphorus) that leave septic system drain fields and are transported to adjacent streams.

STORM WATER RUNOFF: water and associated nutrients (nitrogen and phosphorus) that flow overland during storm/rain events and are washed or discharged directly into streams.

TIPPING POINT: a specific point at which change in an ecosystem becomes extremely rapid in response to an accumulated change in an external variable.

TOTAL SUSPENDED SOLIDS: the concentration of all particles in the water column.