Submerged Aquatic Vegetation in the Mesohaline Region of the Patuxent Estuary: Past, Present, and Future Status

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ABSTRACT: The loss of submerged aquatic vegetation (SAV) from the Patuxent estuary during the latter part of the 20th century was explored using diverse data sets that included historic SAV coverage and distribution data, SAV ground truth observations, water clarity and nutrient loading data, and epiphyte light attenuation measurements. Analysis of aerial photography from 1952 showed that SAV was abundant and widely distributed along the entire mesohaline region of the estuary; by the late 1960s rapid declines in SAV took place following large increases in nutrient loading to the estuary. An examination of water clarity and epiphyte data suggest that the processes that led to the loss of SAV varied in strength along the axis of the estuary. In the upper mesohaline region, Secchi depths were consistently less than established mesohaline SAV habitat requirements at 1-m water depth, suggesting that water clarity was responsible for SAV decline. In the lower mesohaline region, where water clarity was consistently above SAV requirements, high epiphyte fouling rates significantly reduced light available to SAV. Experimental results show that epiphyte fouling had the capacity to reduce available light to SAV blades from 30% to 7% of surface light within a week, and likely contributed to the local decline and near total loss of SAV during the late 1960s and early 1970s. The prognosis for near-term SAV recovery within the mesohaline portion of the estuary seems unlikely given existing water quality conditions.

Introduction

The Patuxent estuary, like many other temperate estuaries, has experienced dramatic declines in the coverage of submerged aquatic vegetation (SAV) during the last half of the 20th century (Den Hartog and Polderman 1975; Orth and Moore 1983, 1984; Cambridge and McComb 1984). Numerous studies suggest that reductions in light available to SAV, as a result of increased nutrient loading to these systems, was the primary cause of these declines (Wetzel and Hough 1973; Philips et al. 1978; Kemp et al. 1983; Dennison and Albert 1986; Twilley et al. 1985). Light available to the SAV blade is attenuated not only by the water column, but also by epiphytes and their associated communities that colonize SAV blades (e.g., Borum 1985; Twilley et al. 1985; Burt et al. 1995). Recent efforts to better assess habitat quality for SAV in Chesapeake Bay have included the effects of epiphyte light attenuation in establishing accurate habitat requirements (Batuik et al. 2000). In the Patuxent estuary, a significant but widely scattered amount of information is available documenting the changes in nutrient loading, water clarity, and SAV coverage that took place during the latter half of the 20th century. Recent studies focusing on

epiphyte light attenuation (Stankelis et al. 1999) provide an important linkage between historical SAV coverage and water quality data to Chesapeake Bay SAV habitat criteria (Batuik et al. 2000). We compare these diverse data sets to gain a better understanding of the processes that led to the decline of SAV, validate current SAV water quality criteria, and provide a prognosis for future recovery.

Land-use History and Estuarine Characteristics

A variety of historical observations and scientific studies indicate that SAV was present and abundant along most portions of the Patuxent estuary until late in the 20th century. Studies using pollen-dated sediment cores found that SAV was continuously present from approximately 1200 AD to the early 1970s at several locations along the estuary (Brush and Davis 1984; Brush and Hilgartner 2000). In addition, historical documents such as "The Old Plantation" (Hungerford 1859, p. 54) describe the Patuxent during the mid-1830s as one of the clearest rivers flowing into the Chesapeake. Passages such as "So transparent are its waters that far out from the shore you may see, in the openings of the sea-weed forest [SAV], on its bottom the flashing sides of the finny tribes as they glide over the pearly sands" give an indication of water clarity during that time. In 1850, approximately 86% of the watershed was agricultural pastureland

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and 14% was forested. By the 1970s, forested lands had risen to 57% of total land area while agricultural use had decreased. In the last 30 years land use has changed even further with urban and residential areas increasing, and forest and agricultural land decreasing (Costanza et al. 1995).

While land use within the watershed (2,400 km²) has changed substantially over the last 150 years, human population growth did not increase rapidly until the second half of the 20th century. In 1900 the total population of the watershed was 28,000, yet had only increased to 37,000 by 1940. Between 1940 and 1970 population increased more than six fold, to 246,000. The present population is in excess of 600,000 and land use is the most urban oriented of all major Chesapeake tributaries (Maryland Office of State Planning 2000). Sewage treatment discharge also increased in association with population growth. Between 1940 and 1980, nutrient loading rates increased with the greatest changes occurring between the late 1960s and mid-1980s. Sewage treatment plant discharges increased from 11,000 m³ d⁻¹ in 1963 to 136,000 m³ d⁻¹ in 1980 and finally to 190,000 m³ d⁻¹ in the late 1990s (Domotor et al. 1989; U.S. Environmental Protection Agency 2002).

Mean annual freshwater input to the estuary at the fall line is 10.6 m⁻³ s⁻¹, which is the sixth largest source of freshwater entering Chesapeake Bay. The estuarine portion of the Patuxent is approximately 65 km in length and has littoral zone habitat sufficient to support SAV in all three salinity zones. The amount of SAV habitat (water depths < 1 m) is not evenly distributed among these regions; there are 20.9 km² capable of supporting SAV in the mesohaline zone, 5.8 km² in the oligohaline zone, and only 2.0 km² of SAV habitat in the tidal fresh zone. Because the mesohaline zone contains the largest area capable of supporting SAV, we focused on changes that occurred within that region of the estuary. This region of the estuary extends from the mouth of the estuary at Drum Point, 35 km upriver to Chalk Point (Fig. 1). During the summer months, median water residence time in the mesohaline portion of the estuary is approximately 35 d (Hagy et al. 2000).

Methods and Analysis

Data from a number of different sources were required in this analysis and included aerial photographs of SAV distribution and coverage, SAV ground truth observations, fall line nutrient loading data, and water quality data collected from numerous studies. Differences among study locations, seasons in which data were collected, and methods of data collection restricted, in some cases, how information could be compared and analyzed. Re-
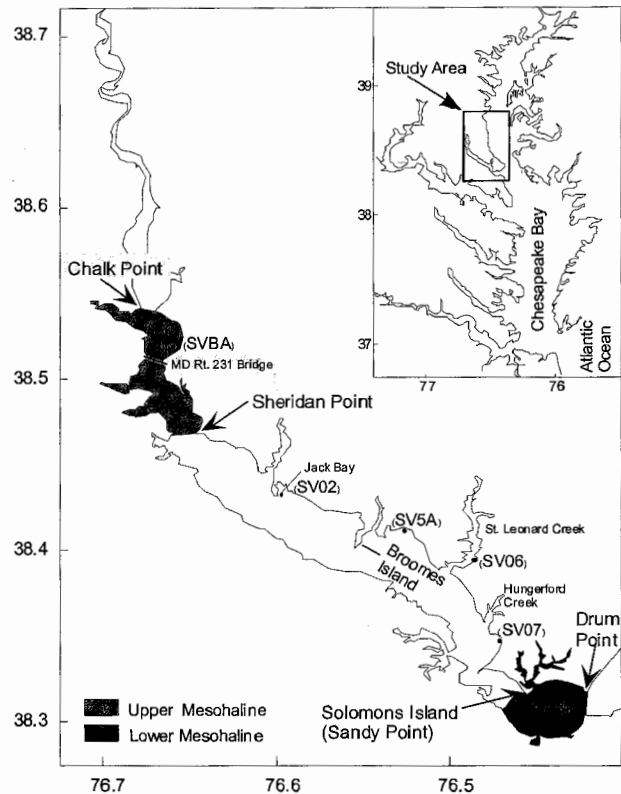

Fig. 1. Mesohaline region of the Patuxent River estuary. Shaded areas represent locations where water quality data were collected. Epiphyte study locations are also shown.

sults of recent studies of light attenuation by epiphytic accumulation on SAV were used to help interpret changes in SAV distribution and provide a link between increases in nutrient loading and SAV decline due to light limitation. These data were also compared to current light-based SAV habitat requirements (Batuik et al. 2000).

INTERPRETATION OF AERIAL PHOTOGRAPHY

Estimates of SAV distribution in the mesohaline region of the Patuxent estuary, prior to the decline of SAV populations, were made by photographic interpretation of historic Soil Conservation District aerial photographs taken in 1938, 1952, and 1964 (National Archives and Record Service unpublished data). Temporal changes in SAV coverage were assessed by comparing these data to similar estimates of SAV coverage collected annually since 1984 by the Virginia Institute of Marine Sciences (VIMS 1999). Photographs from 1952 cover the entire mesohaline portion of the estuary and are directly comparable to data collected in recent years. In 1938 photographs were only available for the region between Chalk Point and Broomes Island. In order to assess changes in the distribution

and coverage of SAV between 1938 and 1952, only those areas in common were compared. Limited photographs of sufficient quality for 1964 were also available for the Broomes Island area as well as Solomons Island and provided additional information concerning the temporal pattern of SAV decline.

For 1952, 24 × 24 inch black and white photographs were digitally scanned at 150 dpi, and georeferenced to orthophoto quarter quadrangle maps. For 1938 and 1962, 9 × 9 positives were scanned at 300 dpi and georeferenced to State Highway Administration and stream layer rasters accurate to quad scale (40'). After georeferencing, a composite image was formed from the most desirable sections of each photo. SAV beds were traced directly upon the scanned images as a vector layer, at an on-screen scale of 12,000:1, with the original positives used to help identify difficult to determine areas. On-screen scales for all photographs were kept at 12,000:1, to provide an on-screen visual image of similar quality to the 24,000:1 photos directly interpreted by VIMS in the current SAV monitoring program. This decision had the effect of generating similar minimum bed sizes and final vectors directly comparable between 1938, 1952, 1964, and those interpreted by VIMS in the more recent surveys (VIMS 1999).

WATER QUALITY AND NUTRIENT LOADING

Secchi depth was chosen as an indicator of water transparency because it was the most commonly collected parameter in the studies reviewed. Although current SAV habitat requirements in Chesapeake Bay are based upon light available at the SAV leaf surface (Batuik et al. 2000), water clarity (Secchi depth) provides a secondary diagnostic tool indicating light penetration to a fixed depth. For comparative purposes we used a water depth of 1 m to convert the minimum water column light requirement of 22% surface light for SAV in the mesohaline zone (Batuik et al. 2000) into a minimum Secchi depth of 1 m.

Since estuaries are temporally and spatially quite heterogeneous, differences in the season and location at which data were collected reduced the amount of data that could be compared. While the SAV growing season typically includes the period April–October (Batuik et al. 2000), data for this comparison were limited to the period between June 15 and September 15 of each year because the majority of data were available for that period. Secchi data were summarized and pooled from two regions within the mesohaline portion of the estuary (Fig. 1). In the upper mesohaline zone, data were collected from sites located between Chalk Point and Sheridan Point. In the lower mesohaline

zone, data from sites located between Sandy Point and Drum Point were used.

Estimates of nutrient loading at the fall line for the period 1960–1977 were reconstructed using river flow, rainfall, and nutrient concentration data (Hagy et al. 1998). Nutrient loading data from 1978 to the present were collected as part of the U.S. Geological Survey Fall Line Monitoring Program.

EPIPHYTE LIGHT ATTENUATION

Estimates of epiphyte light attenuation were made by exposing artificial substrata to natural fouling at six nearshore locations along the mesohaline portion of the Patuxent estuary. These stations were distributed from just above the Maryland Route 231 bridge (SVBA), to Solomons Island (SV09) near the estuary mouth (Fig. 1). Artificial substrata in the form of thin strips of Mylar polyester plastic (2.5 cm × 51 cm × 0.7 mil) were deployed at approximately 1.0-m water depth (mean water depth), on a weekly basis from June through October 1998. Strips were exposed to fouling for periods of 6–8 d during each deployment. Small foam floats (~3.5 × 3.3 cm) were attached to one end of each strip to maintain an upright position in the water column, yet allow the strip to move with water currents. The other end was fastened to a weighted PVC frame placed on the sediment surface. Previous studies using this technique have shown that Mylar strips can be an adequate surrogate for live grass blades for the estimation of epiphyte accumulation during short-term (1 wk), in situ deployments (Stankelis et al. 1999). Estimates of light attenuation due to epiphytic fouling were accomplished by measuring the difference between light flux transmitted through fouled strips and clean unfouled strips. Light flux measurements were made with the light attenuation measurement apparatus (LAMA; Fig. 2). The LAMA consisted of a standard 60 watt light source with a light diffuser screen, a water bath, and a Li-Cor model 192 SA quantum sensor. This configuration was similar to that used by Burt et al. (1995). All light flux measurements were made in 0.2-μm filtered seawater. The Li-192SA quantum photo sensor measures photosynthetically active radiation in the 400–700 nm range. The LAMA was also configured such that light flux reaching the sensor through a blank (clean) strip was in the range of 90–105 μmol m^{-2} s^{-1}. Epiphyte material from both sides of these strips were removed and analyzed for total chlorophyll a (chl a) mass and dry mass per unit area. Estimates of water column light attenuation were also made concurrently with the epiphyte collections at each location and were used in the calculation of percent light through the wa-
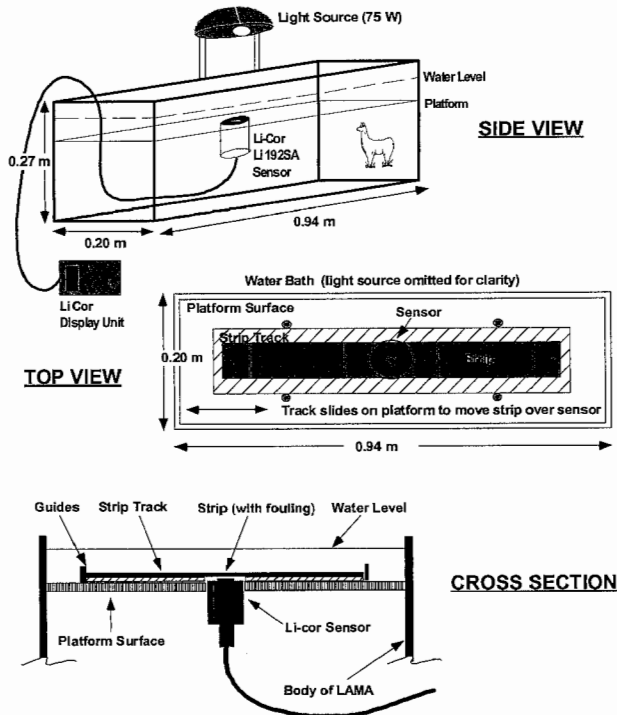
Fig. 2. Diagrammatic sketch of the light attenuation measurement apparatus (LAMA).

Fig. 3. Estimated distribution of SAV in the mesohaline reach of the Patuxent River in 1952. Area upriver of Broomes Island was photographed on June 26. Area below Broomes Island was photographed on October 22.

ter column (PLW), where k_d (m^{-1}) is the water column light attenuation coefficient, and Z (m) is the mean tidal depth.

$$PLW = 100exp[(k_d)(Z)] \qquad (1)$$

In order to include the contribution of epiphyte light attenuation we used the percent surface light reaching the leaf surface (PLL) statistic

$$PLL = PLW[1 - LA/100] \qquad (2)$$

following the method outlined by Batuik et al. (2000), where LA (% light exposure) is the measured epiphyte light attenuation. In this way we were able to compare our estimates to current SAV habitat requirements.

Results

SAV COVERAGE AND DISTRIBUTION IN THE PATUXENT RIVER ESTUARY

Interpretation of the 1938 aerial photographs identified 715 ha of SAV within the area located between Chalk Point and Broomes Island. In comparison, 397 ha were identified in 1952 within the same region of the estuary. Based on detailed evaluation of photos, it appears that differences in total SAV area were due to loss of SAV from the deeper portions of littoral areas. Despite a decline in total coverage between 1938 and 1952, SAV was

still widely distributed along the entire mesohaline region of the Patuxent estuary in 1952 (Fig. 3). While such a change may be consistent with declining water quality, these differences could also be attributed to natural fluctuations in SAV distribution, differences observed between seasons, as well as differences in water quality at the time the photos were taken. For example, the 1938 photos were taken on April 24, while the 1952 photos were taken on June 26. *Zannichellia palustris*, one of the more abundant species in the lower Patuxent, begins to die back in late May, potentially resulting in a lower SAV coverage for photos taken after this time.

A comparison of the SAV coverage of the Broomes Island area among years 1938, 1952, and 1964 indicate SAV coverage in 1964 (133 ha) intermediate between 1938 (217 ha) and 1952 (86 ha; Fig. 4). A similar comparison of SAV coverage of the Solomons area among the same three years indicates virtually no change in distribution or coverage of SAV (Fig. 5). Recent aerial surveys show that even during a minor resurgence in SAV during the mid-1980s, total SAV coverage was a small fraction of that observed a few decades earlier (Fig. 6). Since 1990 only small ephemeral beds have been observed in the mesohaline portion of the estuary. A visual comparison of a low altitude photo of the Solomons area taken in 1938 to a photo taken in 1999 further illustrates the changes in SAV

a) 1938   b) 1952   c) 1964

217 ha   86 ha   133 ha

Fig. 4.   Distribution of SAV around Broomes Island in a) 1938, b) 1952, and c) 1964.

abundance that have taken place during the 20th century (Fig. 7).

In addition to photographic evidence of SAV coverage and distribution in the upper mesohaline portion of the estuary, a series of SAV ground truth

a) 1938

164 ha

b) 1952

160 ha

c) 1964

135 ha

Fig. 5.   Distribution of SAV around Solomons Island in a) 1938, b) 1952, and c) 1964.

Fig. 6.   Estimated SAV coverage in the mesohaline portion of the Patuxent estuary. Area estimated in 1938 represents only a portion of the total SAV habitat, due to lack of interpretable photographs. Data from 1952 and 1975 to 1997 include the whole mesohaline portion of the estuary (VIMS 1999).

observations were made during the 1960s and 1970s. In 1964, Anderson (1969) found large beds of *Ruppia maritima, Potamogeton perfoliatus,* and *Najas flexilis* on both shores of the Patuxent upstream and downstream of the then non-operational Chalk Point power generating station. The following year, after initiation of power-plant operations, Anderson et al. (1968) found the *R. maritima* pop-

Fig. 7.   Aerial view of SAV beds around Solomons Island in 1938 (upper) and 1999 (lower).

Fig. 8.   Mean (± 1 SE) Secchi depth data from two regions within the mesohaline portion of the Patuxent River estuary. Data were collected from June 15 through September 15 of each year. Dashed line represents mesohaline secondary SAV habitat limit (Batuik et al. 2000) using the conversion $k_d = 1.45/$Secchi depth for a depth of 1 m.

Fig. 9.   Estimated Patuxent River annual total nitrogen (TN) and total phosphorus (TP) loading rates measured at the fall line from 1960 to 1995. Data were averaged by 5-year intervals. Adapted from Hagy et al. (1998).

ulation very much reduced and replaced by *P. perfoliatus.* From 1964 to 1968, the Academy of Natural Sciences of Philadelphia (ANSP unpublished data) reported healthy beds of *P. perfoliatus* at Sheridan Point and *Myriophyllum* sp., *Elodea nutallii,* and *Fustuca eliatior* present at lower densities nearby. In 1969 SAV density at Sheridan Point was much reduced compared to previous years, and by 1970, the area was devoid of SAV (ANSP unpublished data). Since that time SAV has not been observed in that region of the river. Aerial photography from the late 1960s is of insufficient quality to compare these observations to other regions of the river.

WATER TRANSPARENCY AND NUTRIENT LOADING

In the upper mesohaline region (Chalk Point to Sheridan Point), Secchi depth data were available for three distinct time periods. The earliest measurements were recorded in 1936 and 1939 (Newcomb and Brust 1940; Nash 1947) during a period when SAV was still abundant in many areas. During this time, mean summer season Secchi depth was greater than 0.75 m (Fig. 8). While this value was below the 1-m Secchi depth regarded as necessary for SAV at the 1-m depth contour (Batuik et al. 2000), SAV was abundant at that time (Fig. 6). Although no field data were found through the 1940s and 1950s, aerial photographs from 1952 show that SAV was still present along many reaches of the estuary suggesting that water quality had not yet deteriorated to where SAV could not survive. The next series of Secchi depth data were available from 1964 through 1974 (ANSP unpublished data). During this period, mean Secchi depth

dropped sharply from a maximum of 1.3 m in 1964 to a minimum of 0.5 m in 1972 (Fig. 8). During this time, large changes in nutrient loading rates were taking place within the estuary. Largely because of increases in sewage discharges, both total nitrogen (TN) and total phosphorus (TP) loads at the fall line more than doubled between 1960 and 1975 (Fig. 9). From 1985 through 1998, mean Secchi depths (U.S. Environmental Protection Agency 2002), while variable, have remained depressed compared to conditions found during the late 1930s, and well below the 1-m Secchi depth needed for healthy SAV at the 1-m depth contour (Batuik et al. 2000).

In the lower mesohaline region (Sandy Point to Drum Point) the earliest known Secchi depth measurements were made in 1937 and 1939 (Newcome and Brust 1940; Nash unpublished data). These data indicate that summer (June 15–September 15) Secchi depth was much greater in the lower river (mean = 1.9 m) compared to the upper mesohaline zone (mean = 0.8 m, Fig. 8). No water transparency data were located from the 1960s and early 1970s. Data collected since 1985 show high interannual variability in water clarity conditions (U.S. Environmental Protection Agency 1999). In 1987, the median summer Secchi depth was 1.9 m while two years later the median summer Secchi depth had decreased to 1.1 m. Despite this variation, water clarity has consistently exceeded that estimated as needed for SAV growth to depths of 1 m (Batuik et al. 2000).

EPIPHYTE STUDIES

Mean epiphyte fouling rates increased linearly from upper to lower mesohaline locations and differed by a factor of six within the whole mesoha-

water column attenuation at these upper mesoha-line locations. At the study site located near Chalk Point (SVBA), summer season fouling only reduced light to the leaf surface an additional 4% of surface radiation, further indicating that water clarity was the primary factor responsible for the local extinction of SAV in this area.

SAV in the lower mesohaline region were exposed to a different set of water quality conditions. While aerial photographs showed that SAV was still present and abundant through the early 1960s, by the late 1960s and early 1970s, SAV around Solomons Island was observed in some years but not in others (Wood personal communication). This suggests that SAV communities, though stressed, were able to maintain minimal recruitment and growth during this time. However, the impact of Hurricane Agnes in June 1972 resulted in major losses of SAV in all regions of the Bay (Orth and Moore 1983). The extreme conditions brought about by this storm were likely a significant contributor to the final local extinction of SAV in this region. Since no data or written documentation of water clarity were available from the late 1960s and early 1970s, we cannot conclude that declining water clarity alone was responsible for the loss of SAV. Secchi depth measurements collected since the mid-1980s indicate that water clarity should be sufficient to support SAV to the 1-m depth contour (Batuik et al. 2000), although persistent SAV populations have not become re-established. During the last few decades, several SAV species have been observed in small patches within this region of the estuary (Moore et al. 2000). These populations have rarely persisted for more than a single season, and in many cases only a few months. In 1997, a bed of *Stukenia pectinata* was found near Hungerford Creek (Fig. 1), but did not survive beyond summer. Similarly, *R. maritima* was observed, in small patches (1–4 m²) along shoreline areas near the mouth of the Patuxent in the summer of 1999. These isolated patches also did not persist into the next season. An exception to this generalization has been the frequent appearance of the early spring annual *Z. palustris*, which has been found in many of the smaller tributaries and along the lower 25 km of the main estuary (Stankelis personal observation). However, this species germinates in late winter (generally February–March) and completes its life cycle by mid-June.

Several mechanisms may explain why these small patches of SAV have not persisted, including waterfowl grazing or disturbance by cownose rays (*Rhinoptera bonasus*). It appears that light attenuation, due to epiphytic fouling of SAV leaves is a significant stress to SAV throughout the lower mesohaline and is the probable mechanism contrib-

uting to the loss of SAV from this area. During the summer, epiphyte accumulation in this area (e.g., SV09) can reduce the amount of light reaching SAV blades from approximately 30% of surface irradiance to less than 7% within a week, which is far below the 15% estimated as needed for continued SAV survival. While an exact determination of light availability to a whole plant would depend on many variables such as leaf age, water depth, and hydrodynamics around the blade, these data show that epiphyte accumulation can have a large impact on light availability to SAV.

Conclusions and Prognosis for Recovery

The qualitative responses of SAV to eutrophication have been examined in a number of field, mesocosm, and laboratory studies. The number of direct and indirect processes that influence the growth, survival, and distribution of SAV make quantitative, in situ predictions much more elusive. Even less well known are the conditions necessary to restore SAV to large areas that have suffered complete losses of SAV populations due to eutrophication (Duarte 1995, 1999).

It appears likely that a variety of factors are limiting the resurgence of SAV in the Patuxent estuary. In the upper mesohaline region, water transparency remains far below what has been estimated as the minimum habitat requirements for SAV (Batuik et al. 2000). Consistent with this, SAV has not been observed in this region since the late 1960s, and the prospects for recovery seem remote, given the persistently poor water clarity conditions in this area. Management actions have reduced nutrient loads to the head of the estuary (Fig. 9) but there has not been a concomitant reduction in turbidity in the upper mesohaline littoral zones.

In the lower mesohaline region, it appears that several factors may be restricting SAV from becoming re-established including epiphyte fouling of SAV, physical disturbances, waterfowl grazing, and lack of a proximal seed source for some species (e.g., *Zostera marina*). It seems very likely that epiphyte-induced light limitation is the primary factor suppressing recovery of SAV, in the same fashion that this mechanism probably caused the massive decline of SAV several decades earlier. Multiple, small (1–16 m²) SAV transplants in the lower mesohaline region all suffered severe epiphytic fouling and transplants have not persisted beyond a year or two. Small, naturally occurring beds of other species (e.g., *S. pectinata*) have been observed in recent years but these also rapidly fouled and none have persisted more than a single season. Small, newly established SAV beds may be particularly sensitive to grazing pressure from non-native mute swans (*Cygnus olor*) and physical disturbance by

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