

Distribution and Abundance of Submersed  
Aquatic Vegetation in the Tidal Potomac  
River and Estuary, Maryland and Virginia,  
May 1978 to November 1981

A Water Quality Study of the  
Tidal Potomac River and Estuary

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By Virginia Carter, James E. Paschal, Jr.,  
and Nancy Bartow

*To Wandy  
Keep up the good work!  
I want reports & thanks  
[unclear]*

DEPARTMENT OF THE INTERIOR  
WILLIAM P. CLARK, Secretary

U.S. GEOLOGICAL SURVEY  
Dallas L. Peck, Director



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## CONVERSION FACTORS

**For use of readers who prefer to use inch-pound units, conversion factors  
for terms used in this report are listed below:**

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
<b>Length</b>		
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281 1.094	foot (ft) yard (yd)
kilometer (km)	0.6214 0.5400	mile (mi) nautical mile (nmi)
meter per second (m/s)	3.281	foot per second (ft/s)
nanometer (nm)	$3.937 \times 10^{-8}$	inch (in)
<b>Area</b>		
square meter (m <sup>2</sup> )	10.76 1.196	square foot (ft <sup>2</sup> ) square yard (yd <sup>2</sup> )
<b>Volume</b>		
cubic meter (m <sup>3</sup> )	35.31 1.308	cubic foot (ft <sup>3</sup> ) cubic yard (yd <sup>3</sup> )
liter (L)	1.057	quart (qt)
cubic meter per second (m <sup>3</sup> /s)	35.31	cubic foot per second (ft <sup>3</sup> /s)
<b>Mass</b>		
milligram (mg)	0.00003527	ounce (oz)
gram (g)	0.03527 0.002205	ounce (oz) pound (lb)
kilogram (kg)	2.205	pound (lb)
metric ton (Mg)	2,205 1.102	pound (lb) ton (short)
gram per square meter (g/m <sup>2</sup> )	8.922	pound per acre (lb/acre)
<b>Temperature</b>		
degree Celsius (°C)	1.8 (+ 32°)	degree Fahrenheit (°F)
<b>Concentration</b>		
milligram per liter (mg/L)	1.0	parts per million (ppm)
grams per liter (g/L)	1.0	parts per thousand (ppt)
<b>Symbol</b>	<b>Meaning</b>	<b>Conversion</b>
PAR	Photosynthetically active radiation (400-700 nanometer waveband). Measured in microeinsteins per square meter per second[( $\mu\text{E}/\text{m}^2/\text{s}$ )]	full sunlight is approximately 2,000 ( $\mu\text{E}/\text{m}^2$ )/s foot candle = $1.78 \times 10^{-21} \mu\text{E}$
$\mu\text{mho}$	Conductance in micromhos. A measure of the amount of dissolved ions present in water	1 part per thousand is approximately 1,500 $\mu\text{mho}$ at 25°C
( $\text{E}/\text{m}^2$ )/s	Radiometric unit of measure	1 ( $\mu\text{E}/\text{m}^2$ )/s = 0.2174 watts/m <sup>2</sup> assuming a flat spectral distribution curve for the light over the 400-700 nanometer range

# Distribution and Abundance of Submersed Aquatic Vegetation in the Tidal Potomac River and Estuary, Maryland and Virginia, May 1978 to November 1981

By: Virginia Carter, James E. Paschal, Jr. and Nancy Bartow

## ABSTRACT

The distribution and abundance of submersed aquatic vegetation in the tidal Potomac River and Estuary were studied from 1978 through 1981 with the assistance of the U. S. Fish and Wildlife Service. Sixteen species of submersed aquatic plants were identified, fourteen vascular plants and two species of the algae *Chara*. Most of the plants were located in the transition zone of the Potomac River and Wicomico River tributary, with a few isolated populations in the tidal river and estuary. *Vallisneria americana*, *Zannichellia palustris*, *Ruppia maritima*, and *Potamogeton perfoliatus* were the most abundant and widespread species. The present distribution and abundance differ considerably from that in the early 1900's when flats in the tidal river were covered with lush vegetation including *Vallisneria* and *Potamogeton* spp., and the estuary had an abundance of *Zostera marina*.

The factors responsible for the decline of submersed aquatic vegetation in the tidal Potomac River and Estuary are varied and complex. The most likely reasons for the almost complete disappearance of these plants from the tidal river include extensive storm damage in the 1930's; increasing nutrient enrichment with a shift in the relationship or balance between submersed aquatic plants and phytoplankton; a change in light availability; and grazing by turtles, fish, muskrat, or waterfowl before an adequate rhizome mat or minimum bed size is established. Salinity dynamics in the transition zone may account for the presence of abundant vegetation and the diversity of species in this area.

## INTRODUCTION

The U.S. Geological Survey began a comprehensive interdisciplinary study of the tidal Potomac River and Estuary in Maryland, Virginia, and the District of

Columbia in 1977. The project included extensive water quality sampling and studies of geology, bathymetry, sedimentation, hydrodynamics, geochemistry of bottom sediments, transport of dissolved and suspended materials, oxygen demand during low-flow conditions, bacterial and phytoplankton dynamics, benthic community structure, and submersed aquatic vegetation. The overall goal of the combined effort was to understand the major aspects of hydrodynamic, chemical, and biological processes and their interaction in a tidal river-estuarine system (Blanchard and Hahl, 1981, p.2).

In 1978, the U.S. Geological Survey and the Migratory Bird Habitat Research Laboratory of the U.S. Fish and Wildlife Service (FWS) began a cooperative study of the distribution and abundance of submersed aquatic vegetation in the riverine and estuarine environments of the tidal Potomac River. The Geological Survey and FWS performed cooperative surveys of submersed aquatic vegetation during 1978 and 1979. The Geological Survey continued the survey through 1980 and 1981 and performed experiments in the laboratory and field to identify factors affecting the distribution and abundance of submersed aquatic vegetation. The objectives of the submersed aquatic vegetation study were:

1. To document the present distribution and abundance of submersed aquatic vegetation in the tidal Potomac River and estuary.
2. To compare the present distribution of submersed aquatic vegetation with the historic distribution.
3. To identify factors responsible for the present distribution of submersed aquatic vegetation.



4. To consider the implications of the present distribution and abundance of submersed aquatic vegetation to water quality and riverine and estuarine ecology.

This report presents the results of the submersed aquatic vegetation study. Because of the multiple objectives of the project, the methods and the results sections are subdivided into sections on (1) submersed aquatic vegetation distribution and abundance, (2) submersed aquatic vegetation transplants, and (3) factors affecting distribution and abundance.

Many factors, both natural and man related, have been implicated in the decline of submersed aquatic vegetation populations in the Potomac River, Chesapeake Bay, and in other aquatic ecosystems (Mills and others, 1966; Stevenson and Confer, 1978; Phillips and others, 1978; Haslam, 1978; Stevenson and others, 1979). Some of these factors, such as herbicides and chlorine, were beyond the scope of this project.

## Background

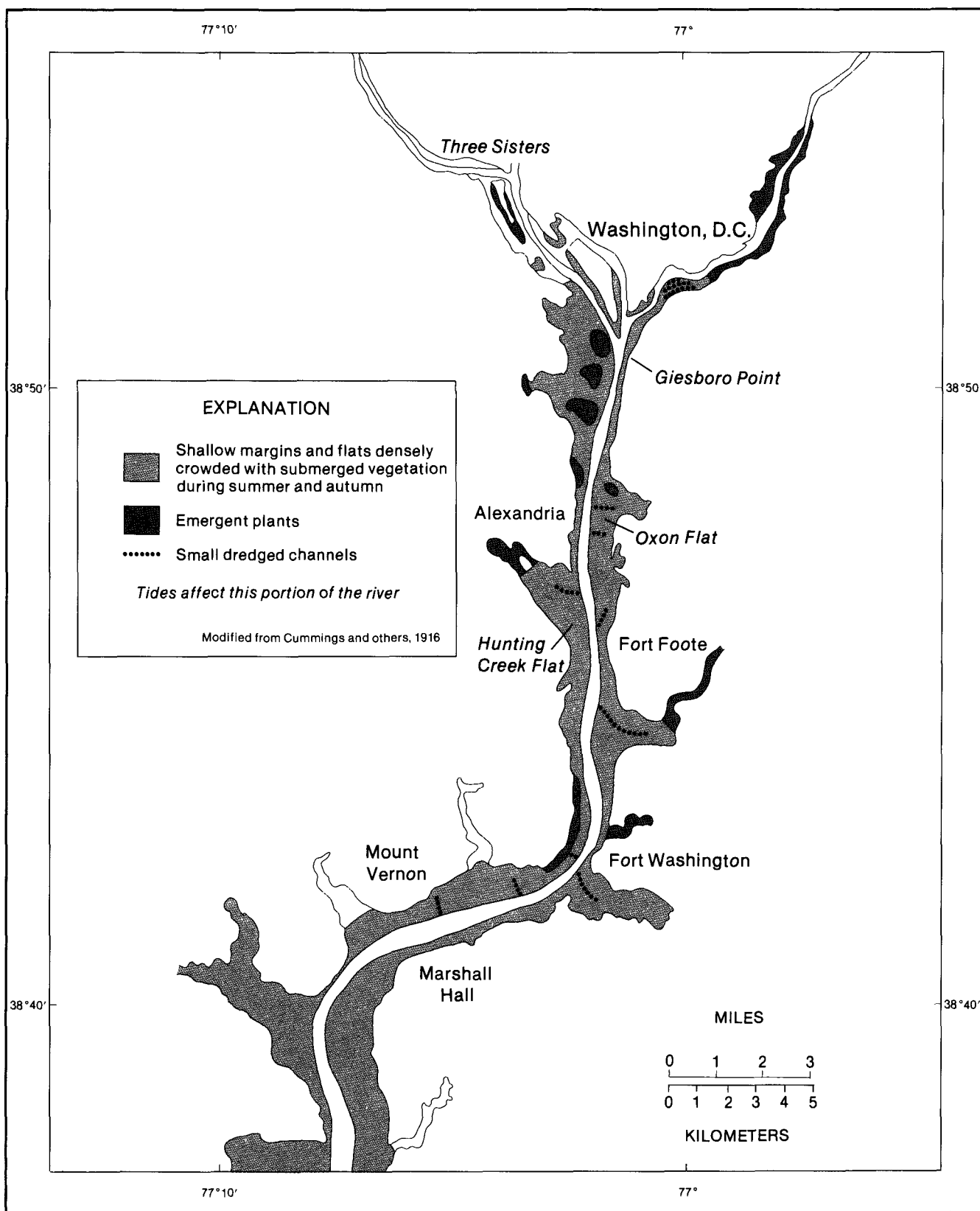
Submersed aquatic macrophytes are one important biological component of coastal ecosystems such as the Chesapeake Bay and the Potomac River. Whether growing in beds along the littoral zone or floating in detached masses moved by tidal currents, submersed aquatic vegetation provides a habitat for large numbers of small invertebrate species which are eaten by waterfowl, fish, and larger invertebrates. The plants themselves form the base of the detrital and macrophyte food chains. Seeds, leaves, stems, tubers, and epiphyte populations on leaves and stems are consumed by such diverse species as ducks, muskrats, snails, and turtles (Martin and Uhler, 1939; Lippson and others, 1979). Submersed aquatic vegetation provides shelter for juvenile fish, turtles, and macroinvertebrates such as scallops, shrimp, and crabs (Orth and others, 1979). The stems and leaves retard current flow and the roots stabilize the bottom, thus slowing erosion and causing the sediments to accumulate (Allen, 1979; Boynton and Heck, 1982). Submersed aquatic vegetation has also been cited for its role in oxygenating the water (Cumming and others, 1916; Secretary of the Treasury, 1933; Haslam, 1978; Korsak and Myakushko, 1981), in reducing nutrient concentrations (Boynton and Heck, 1982) and in cycling nutrients from the sediments to the overlying water (McRoy and McMillan, 1977).

## Historical Distribution

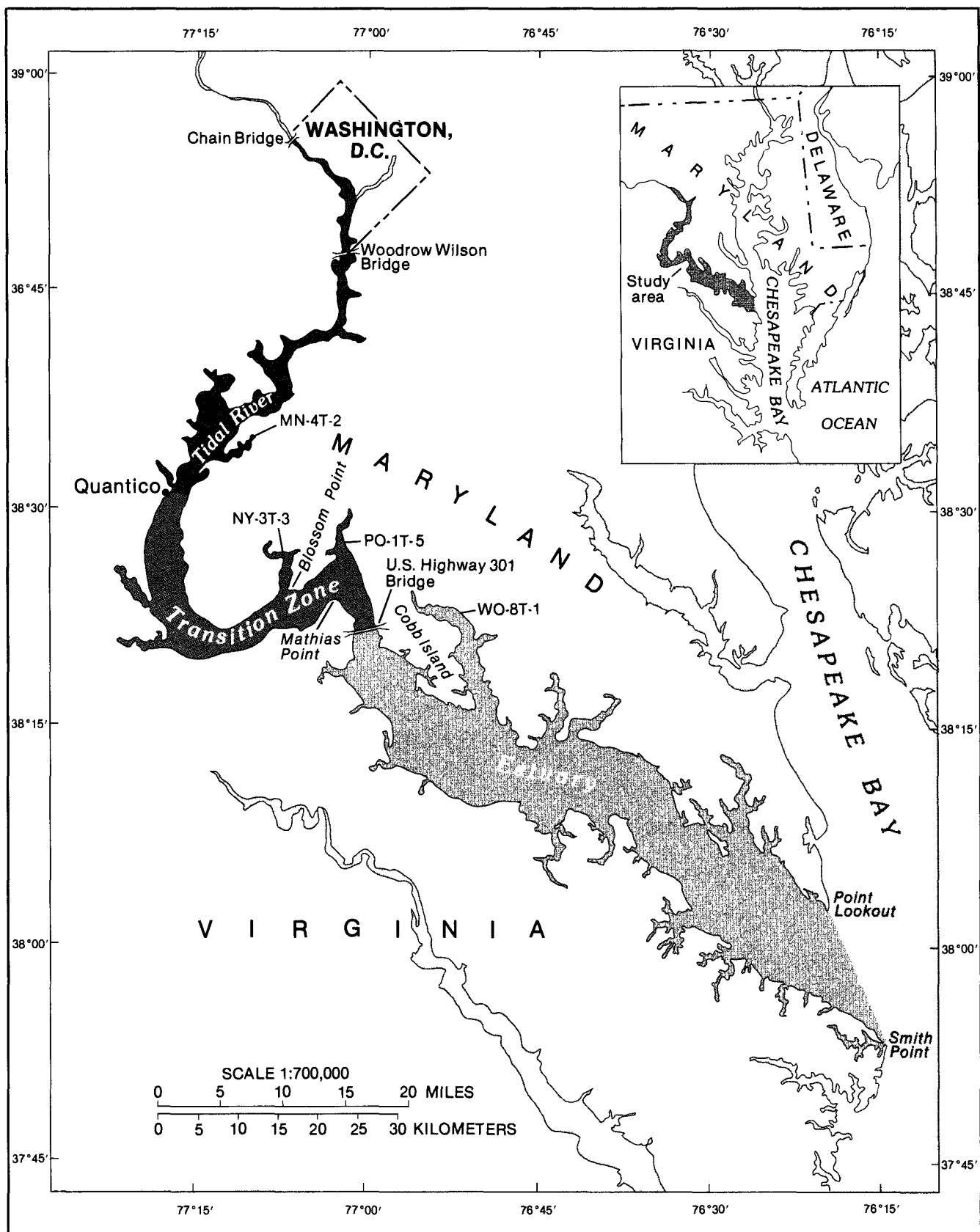
Historically, the Potomac Estuary and freshwater tidal river contained numerous species of aquatic

macrophytes in abundance. Seaman (1875) reported *Vallisneria spiralis* (*V. Americana* Michx.; wildcelery), *Ceratophyllum demersum* (coontail), *Najas flexilis* (naiad), and *Anacharis alcinastum* (old world elodea) in the vicinity of Washington, D.C. The U.S. Coast and Geodetic Survey Rosier Bluff to Glymont maps for 1904 bear the legend "grass" on all of the shoal areas on the Virginia and Maryland shores of the tidal river. In Gunston Cove, Virginia, the "grass" extended from shore to shore. A 1916 map of the river at low tide (fig. 1) shows a narrow channel and wide shallow vegetated margins and flats containing beds of *Potamogeton crispus* (curly pondweed), *Ceratophyllum*, and *Vallisneria*. Hitchcock and Standley (1919) reported additional species of pondweed in the mouths of the tributaries below Washington, D.C. *Zostera marina* (eelgrass) was once abundant in the estuary up to the vicinity of Cobb Island (fig. 2); it disappeared from the Potomac estuary and many other Atlantic coast estuaries during the late 1930s. In 1933, it was reported that Oxon flat and Hunting Creek flat, two shallow embayments near Alexandria, Va., still contained an abundance of submerged plants including "eel-grass", *Ceratophyllum*, *Potamogeton crispus* and "two or three kinds" of unidentified water grasses (Secretary of the Treasury, 1933).

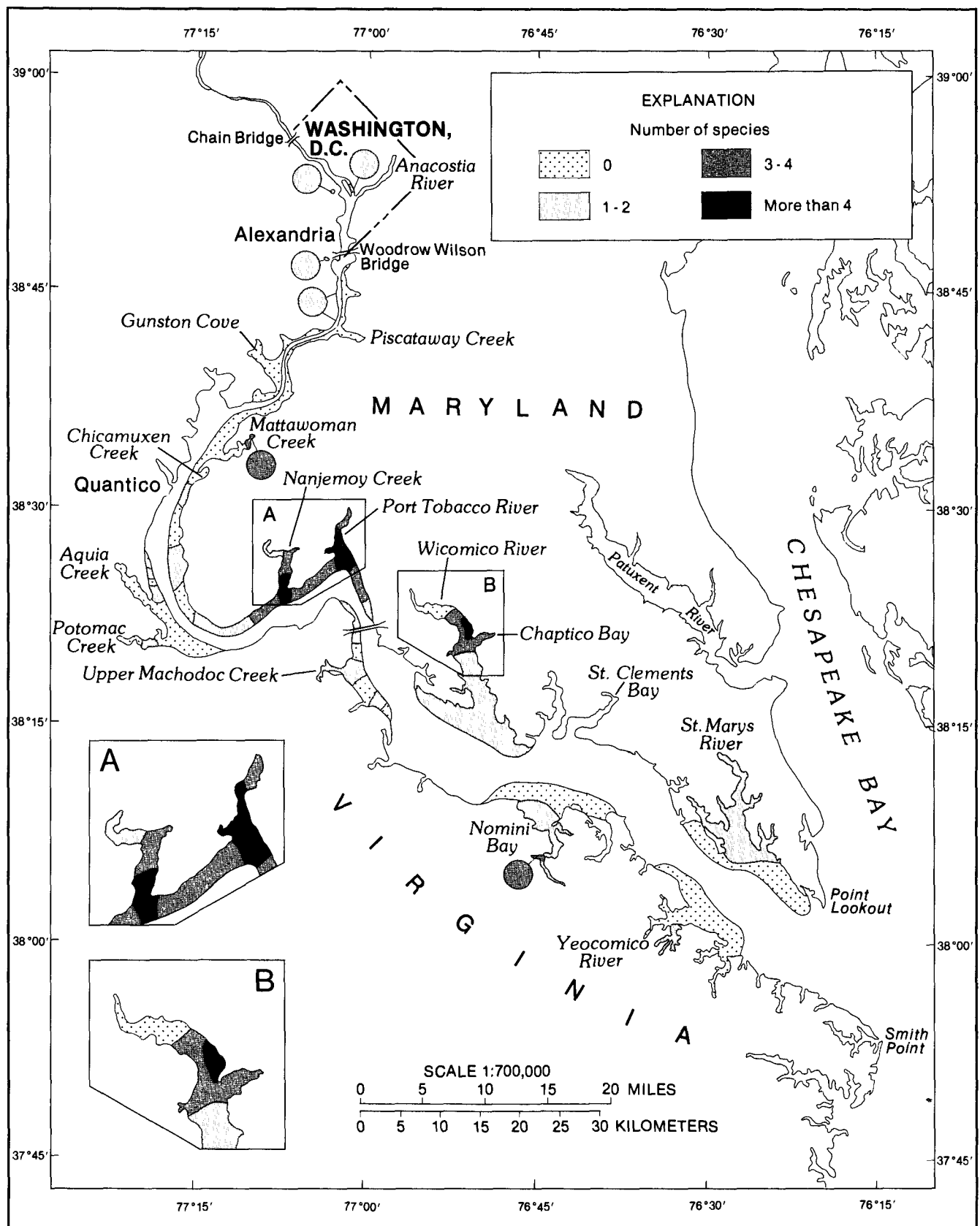
The results of vegetation surveys since the 1950's, as well as historical documentation, herbarium records, and personal observations show that populations of submersed aquatic plants in the Chesapeake Bay and its tributaries, including the Potomac River, have declined in recent years (Bayley and others, 1968, 1978; Elser, 1969; Southwick and Pine, 1975; Kerwin and others, 1976; Munro, 1976; Stevenson and Confer, 1978; Orth and others, 1979). Bartsch (1954) and Stewart (1962) reported that the upper Potomac (tidal reach above Chicamuxen Creek, fig. 3) which once had extensive beds of *Vallisneria*, *Najas guadalupensis* (southern naiad), and *Potamogeton pectinatus* (sago pondweed) was devoid of submersed vascular plants. Stewart found an abundance of submersed aquatic plants in the central Potomac River (Nanjemoy Creek - Port Tobacco River area, fig. 3), but reported only narrow zones of submersed plants in the lower Potomac River (estuary). Orth and others (1982) state that eelgrass was temporarily abundant in the estuary in 1965, more than 30 years after its disappearance. In 1972, 1973, 1977, and 1978, personnel of the Fish and Wildlife Service (FWS) found no submersed aquatic vegetation in the tidal river; only four percent of 150 sampling stations on the tidal river and estuary were found vegetated (Haramis, 1977; personal communication, G.M. Haramis, FWS, 1978). The loss of submersed aquatic vegetation from the tidal river probably occurred in the 1930's because by 1939, Martin and



**Figure 1.** Upper part of tidal Potomac River at low water showing distribution of aquatic vegetation in 1916 (modified from Cumming and others, 1916).



**Figure 2.** The tidal Potomac River, transition zone, and Estuary. Locations of transects MN-4T-2, NY-5T-3, PO-IT-5, and WO-8T-1 are shown.



**Figure 3.** Distribution and number of species of submersed aquatic vegetation in the tidal Potomac River and Estuary during 1978-81. Circles represent vegetation found during informal sampling period.

Uhler (1939) noted the loss of aquatic plants. No comprehensive survey of submersed aquatic vegetation in the tidal river and estuary had been conducted prior to 1978.

## STUDY SITE

The Potomac River is the second largest tributary entering the Chesapeake Bay in terms of drainage area and discharge, contributing about 18 percent of the total freshwater inflow (Pritchard, 1952). The Potomac River enters the western side of the Chesapeake Bay between Point Lookout and Smith Point (fig. 2) and the tidal section extends 183 km from the mouth to Chain Bridge in Washington, D.C. The tidal Potomac River can be divided into three zones: (1) the tidal river above Quantico, Virginia, where the water is fresh except in extremely dry years and the net flow is directed seaward at all depths, (2) the transition zone of the estuary where salinity is low (oligohaline to mesohaline) and extensive saltwater-freshwater mixing occurs, and (3) the lower mesohaline estuary (herein referred to as estuary) which exhibits an internal circulation with reverse bottom flow, strong tidal currents, moderate vertical stratification, and considerable longitudinal variation in salinity (Elliott, 1976; Wilson, 1977). The tidal Potomac River and Estuary are relatively shallow with an overall average depth of 6 m. The greatest depth, about 36.5 m, is found near Mathias Point. Both the tidal river and estuary generally have a deep channel flanked on one or both sides by wide shallow flats or shoals.

## METHODS

### Submersed Aquatic Vegetation Survey

Vegetation-sampling transects were established systematically in each of nine regions selected for study. A region includes one or two tributaries and the main river on either side of the tributary mouth(s). During 1978, 132 transects in four Maryland regions were sampled intensively: (1) the Piscataway-Mattawoman Creeks region in the tidal river, (2) the Nanjemoy Creek-Port Tobacco River region in the transition zone (inset A), (3) the Wicomico River region in the estuary (inset B), and (4) the St. Mary's River region in the estuary (fig. 3). The Wicomico River, which receives substantial freshwater runoff, retains a fresh to salt gradient and thus was divided into transi-

tion zone and estuary. In contrast, the St. Mary's River receives little fresh water from a small watershed, is essentially iso-saline for its major distance, and is perhaps better described as an embayment than a true river. Five sites in Washington, D.C., were sampled in the summer of 1978, but were not resampled in the following years.

In 1979, sampling was repeated on the 132 transects on the Maryland side and extended to 108 transects in five regions on the Virginia side (fig. 3): (1) the Gunston Cove region in the tidal river, (2) the Aquia-Potomac Creek and (3) Upper Machodoc Creek regions in the transition zone; and (4) Nomini Bay, and (5) Yeocomico River regions in the estuary. The upper Machodoc Creek region overlaps both transition zone and estuary; it was placed in the transition zone because of its vegetative composition.

The 1979 survey showed that submersed aquatic vegetation was distributed similarly on both sides of the river, but was less abundant on the Virginia side. Consequently, only the Maryland side was sampled during 1980 and 1981 in order to document changes in biomass and species composition. In 1980, only 103 of the original 132 Maryland transects were resurveyed; 29 of the transect sites in the Mattawoman-Piscataway Creeks region were not resampled because there had been no indication of plant growth at those sites during 1978 or 1979. One transect was established in Washington Channel, four transects were added between Piscataway and Mattawoman Creeks, one new transect was added 5 km up the tributary from the mouth of Mattawoman Creek, the five transects were retained south of Mattawoman Creek on the main river, and ten sites were added in the transition zone from below Quantico, Va., around Maryland Point. During 1981, the original 132 Maryland transects and the 16 Maryland transects established in 1980 were resampled. Maps showing the exact location of each transect can be found in Paschal and others (1982). River kilometers were measured from the mouth of the Potomac River and tributary kilometers were measured from the mouth of the tributary.

Data on vegetation and substrate composition were collected by seasonal sampling along transects running perpendicular to shore for a maximum of 300 m. Transect sites were chosen at 1.85-km intervals (1 nautical mile intervals) along the main river for 7.40 km on either side of tributary mouths. Because of a more changeable shoreline in the tributaries, a minimum of two and a maximum of five transects were selected at each 1.85-km interval along tributaries to include representative shoreline features and related exposures. Sampling was discontinued when tributaries became too shallow for boats or where only a narrow channel remained between emergent wetlands.

# FOREWORD

Tidal rivers and estuaries are very important features of the Coastal Zone because of their immense biological productivity and their proximity to centers of commerce and population. Most of the shellfish and much of the local finfish consumed by man are harvested from estuaries and tidal rivers. Many of the world's largest shipping ports are located within estuaries. Many estuaries originate as river valleys drowned by rising sea level and are geologically ephemeral features, destined eventually to fill with sediments. Nutrients, heavy metals, and organic chemicals are often associated with the sediments trapped in estuaries. Part of the trapped nutrients may be recycled to the water column, exacerbating nutrient-enrichment problems caused by local sewage treatment plants, and promoting undesirable algae growth. The metals and organics may be concentrated in the food chain, further upsetting the ecology and threatening the shell and finfish harvests. Our knowledge of the processes governing these phenomena is limited and the measurements needed to improve our understanding are scarce.

In response to an increasing awareness of the importance and delicate ecological balance of tidal rivers and estuaries, the U.S. Geological Survey began a 5-year interdisciplinary study of the tidal Potomac River and Estuary in October of 1977. The study encompassed elements of both the Water Resources Division's ongoing Research and River Quality Assessment Programs. The Division has been conducting research on various elements of the hydrologic cycle since 1894 and began intense investigation of estuarine processes in San Francisco Bay in 1968. The River Quality Assessment program began in 1973 at the suggestion of the Advisory Committee on Water Data for Public Use which saw a special need to develop suitable information for river-basin planning and water-quality management. The Potomac assessment was the first to focus on a tidal river and estuary. In addition to conducting research into the processes governing water-quality conditions in tidal rivers and estuaries, the ultimate goals of the Potomac Estuary Study were to aid water-quality management decision-making for the Potomac, and to provide other groups with a rational and well-documented general approach for the study of tidal rivers and estuaries.

This interdisciplinary effort emphasized studies of the transport of the major nutrient species and of suspended sediment. The movement of these substances through five major reaches or control volumes of the tidal Potomac River and Estuary was determined during 1980 and 1981. This effort provided a framework on which to assemble a variety of investigations:

(1) The generation and deposition of sediments, nutrients, and trace metals from the Holocene to the present was determined by sampling surficial bottom sediments and analyzing their characteristics and distributions.

(2) Bottom-sediment geochemistry was studied and the effects of benthic exchange processes on water-column nutrient concentrations ascertained.

(3) Current-velocity and water-surface-elevation data were collected to calibrate and verify a series of one- and two-dimensional hydrodynamic flow and transport models.

(4) Measurements from typical urban and rural watersheds were extrapolated to provide estimates of the nonpoint sources of sediments, nutrients, and biochemical oxygen demand during 1980 and 1981.

(5) Intensive summertime studies were conducted to determine the effects of local sewage-treatment-plant effluents on dissolved-oxygen levels in the tidal Potomac River.

(6) Species, numbers, and net productivity of phytoplankton were determined to evaluate their effect on nutrients and dissolved oxygen.

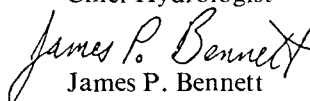
(7) Wetland studies were conducted to determine the present-day distribution and abundance of submersed aquatic vegetation, and to ascertain the important water-quality and sediment parameters influencing this distribution.

(8) Repetitive samples were collected to document the distribution and abundance of the macrobenthic infaunal species of the tidal river and estuary and to determine the effects of changes in environmental conditions on this distribution and abundance.

The reports in this Water-Supply Paper series document the technical aspects of the above investigations. The series also contains an overall introduction to the study, an integrated technical summary of the results, and an executive summary which links the results with aspects of concern to water-quality managers.



Philip Cohen  
Chief Hydrologist



James P. Bennett  
Potomac Study Coordinator

Locations of transects were marked on nautical charts, and transects were sampled by placing a rope with buoys perpendicular to the shoreline. Most transects had stations at 0.5 m and 15 m from shore, and then at intervals of 15 m thereafter. During 1978, transects generally were terminated at 2.5 m depth at high tide, 2-m depth at low tide, or when 300 m of linear distance from the high-tide mark on the beach was reached. Results of the 1978 season showed that if transects were vegetated, the first vegetated station occurred within 60 m of shore. Therefore, sampling was modified during the following years to terminate at the fifth station from shore (60 m) where no vegetation was present. When vegetation was present, sampling was continued to the second of two stations (30 m) beyond the last vegetated station. Where water depth gradients exceeded 2.0 m depth in 60 m of linear distance, samples were taken at approximately 0.5-m depth increments and distance from shore was recorded.

In order to make valid comparisons between the long transects done in 1978 and those done in succeeding years, the number of 1978 transect stations was truncated. The number of stations on vegetated transects was set at two non-vegetated stations beyond the last vegetated station; a minimum of five stations were sampled. On nonvegetated transects, the number of stations was reduced to four (2 m in depth) or five (60 m from shore).

Stations were sampled with modified oyster tongs (Sincock and others, 1965, p. 26; Kerwin and others, 1976; Davis and Brinson, 1976) with blades welded across the teeth to facilitate biting into the sediment and collecting rooted plants. The area sampled by each grab was about 0.093 m<sup>2</sup>. This method is well suited for quantitative sampling where the areal coverage of the study is large and where scuba diving methods are precluded by high turbidity. Samples collected by oyster tongs are comparable to samples taken with a grapple or a grab sampler. All above-ground biomass and a small part of the below-ground biomass were collected with this method. Three grabs were made at each sampling station along transects and water depth and presence or absence of vegetation were recorded for each grab. Sampling was conducted in spring (May-June), summer (July-August), and fall (September-October) of 1978, 1980, and 1981. During 1979, sampling was only conducted during spring and fall because of the additional work involved in sampling the Virginia side. During the summer of 1981, sampling was only done on transects that had previously had three or more species present, and a survey was conducted of the previously unsampled shoreline of the tidal river to locate other beds of submersed aquatic vegetation.

Sampled vegetation was identified to species, and live, wet volumes per grab per species were taken as a measure of relative biomass. Taxonomic nomenclature follows Hotchkiss (1950, 1967), Wood (1967), Radford and others (1974) and Godfrey and Wooten (1979). Trace amounts of vegetation were estimated to be 2.0 mL. Generally very little root or rhizome material was included; many of the species considered had very small roots and did not form a large root mat as the season progressed. If filamentous algae were attached, as much as possible was removed before measurement. When removal was impossible, the amount of algae was estimated as a percentage of the total mass of plant material and that percentage was subtracted from the total volume. To obtain volume to biomass equivalents for each species, 10 to 12 samples were taken from the river during different seasons (if available). Wet weight (most of the water shaken off) and dry weight (oven dried at 110°C for two hours) were measured for specific volumes of each species. These biomass equivalents were used to calculate the biomass differences between regions of the river. Biomass comparisons were done only for the original 1978 transects in the Maryland regions and do not include substituted or additional transects from 1980 and 1981. Biomass per square meter was calculated by dividing the total biomass by 0.093 times the total number of grabs for a transect, region, or salinity zone.

The biomass data presented in this paper were used to establish seasonal and year-to-year trends. Biomass was measured using a volume displacement method (see Mountford, 1980 for a similar technique) and converting to grams of dry weight. It is generally considered more accurate to measure wet and dry weights directly, but the necessity for spending 2 to 3 weeks in the field on each survey made it impossible to dry the vegetation before it rotted. Most of the plants had very little root or rhizome material attached and several species were represented by very small samples. Spring and summer dry-weight determinations (biomass equivalents) were made for *Potamogeton crispus* which has winter buds in the summer and fall and for *Vallisneria*, the most abundant species measured. The biomass data were collected at the same time each year and it was felt that the accuracy achieved was sufficient for purposes of this study.

In addition to the formal sampling program, numerous observations were made on the location and species composition of submersed aquatic vegetation populations and their time of flowering and seed production.



## Factors Affecting Distribution and Abundance

The investigation of factors affecting distribution and abundance of submersed aquatic vegetation involved both laboratory and field studies. These factors included basic data on nutrient and chlorophyll *a* concentrations, discharge, temperature, salinity, specific conductance, pH, and light penetration collected during this project or by other scientists in the Potomac Estuary Study. Methods used to collect and analyze the collateral data from other studies can be found in Blanchard and Hahl (1981). Methods for collecting and analyzing of data from field and laboratory studies are explained below.

Basic data were collected at many sites in the tidal river and estuary. These included seven intensive data collection sites selected to compare transplanted and naturally-vegetated sites in the tidal river and transition zone. The location of these intensive sites--Washington Channel, Goose Island, Rosier Bluff, Elodea Cove, Neabsco Bay, Nanjemoy Creek and Blossom Point--are shown in figures 3 and 4.

### Salinity, Specific Conductance, Temperature, and pH

Salinity, specific conductance, and temperature were measured at selected transect locations with an industrial RS 5-3 Induction Salinometer and a YSI Model 33 S-C-T-meter.<sup>1</sup> During 1978, pH was measured with an X-rite field meter. Specific conductance measurements in the laboratory were made with a Beckman Model RA-2A conductivity meter. Specific conductance, pH, and temperature were measured in the field by other Potomac Estuary project scientists using a Hydrolab Surveyor 6 water-quality monitor.

### Water Depth

Water depth was measured at transect stations and other sites, but was not corrected for tidal stage.

### Substrate

Substrate composition on transects was estimated in the field from visual and tactile characteristics. Substrate samples were collected at transect and other sites to determine particle-size distribution and nutrients; the samples were collected with a plexiglass tube

or a post hole digger, and were sent to the U.S. Geological Survey laboratories for analysis. The following analyses were performed: (1) particle size distribution, (2) nutrient (nitrogen and phosphorus) concentrations, (3) heavy-metal concentrations, and (4) organic-carbon concentrations (American Public Health Association and others, 1975; Skougstad and others, 1979).

### Light Penetration and Water Transparency

A Secchi disk was used to measure Secchi-disk transparency. Secchi-disk data were analyzed for significant differences between zones and seasons by two-factorial analysis of variance (ANOVA) and Duncan's multiple range test (Duncan, 1951, and Kramer, 1956).

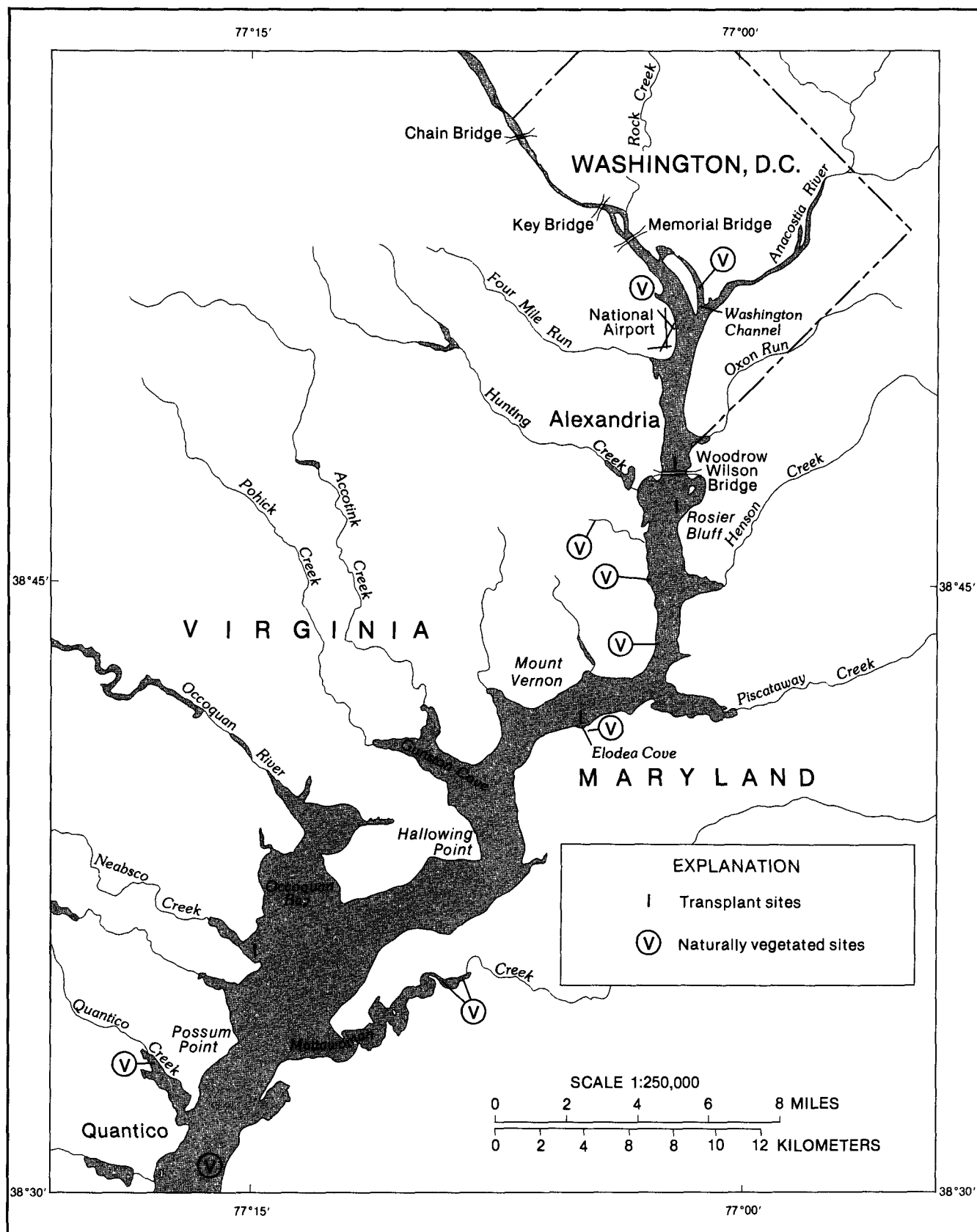
During 1981, photosynthetically active radiation (PAR) of wave lengths of 400-700 nm was measured at selected sites with a LICOR 185B Quantum radiometer-photometer. An underwater sensor with a 3-m cable was used, and light energy in microeinsteins per square meter per second ( $\mu\text{E}/\text{m}^2/\text{s}$ ) was measured above the water surface, just below the surface, and at 200 mm increments below the surface. At some of the sites, water samples were collected to correlate chlorophyll *a* concentrations with light penetration. Chlorophyll *a* was extracted through glass-fiber filters with a 90 percent acetone solution, and the extracts were analyzed using a fluorometer (Woodward, 1982). Reported chlorophyll *a* values are corrected for the presence of phaeophytin, a degradation product of chlorophyll *a* which interferes with the analysis.

### Epiphytes

Epiphytes were collected in the tidal river and estuary during 1981. Artificial substrates (Greeson and others, 1977) were made from strips of transparent polyvinyl lay-flat tubing 270 mm long, 30 mm wide, and 0.04 mm thick, and sealed at both ends. Three artificial substrates were tied to a section of galvanized wire mesh that was, in turn, fastened to a cinder block. A small piece of styrofoam was attached to each strip for flotation. Twice during the spring and summer, and once during the fall, cinder blocks with substrates were placed near shore at each of nine sites. The substrates were left at each site for about two weeks, and then were collected and placed in plastic bags filled with river water. Three samples were taken from each strip with a paper punch, and the three samples were placed together in a 15-mL vial of acetone for chlorophyll *a* and phaeopigment analysis (Woodward, 1982).

<sup>1</sup> Use of brand names is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.





**Figure 4.** Intensive data collection sites (transplanted and naturally vegetated) and other naturally-vegetated sites in the tidal Potomac River. See figure 2 for location in relation to the study area.

Light transmittance through colonized strips was measured in the laboratory with the LICOR photometer; and epiphytes were then scraped from one side of each polyvinyl strip. The scrapings were used to determine dry weight, organic weight, and ash weight (Greeson and others, 1977).

## Heavy Metals

### Field Studies

To determine the effects of heavy metals on submersed aquatic vegetation distribution, sediment samples were collected in different areas of the river. Analyses for arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), mercury (Hg), selenium (Se), and zinc (Zn) were run on sediment samples from vegetated and unvegetated sites in Nanjemoy Creek. Samples from sites in the tidal river and transition zone were analyzed for Zn, Mn, and Pb. All analyses were conducted by the U.S. Geological Survey Central Laboratory (American Public Health Association and others, 1975; Skougstad and others, 1979).

### Laboratory Studies

To determine the effect of Pb, Zn, and Mn on the growth of submersed aquatic vegetation, *Vallisneria americana* was grown in the laboratory. Plants were placed in 4000-mL beakers containing 500 mL of clean sand and 3000 mL of modified Hoagland's solution (Lee and others, 1976); five plants ranging from 110 to 540 mm in length were weighed and planted in each beaker, and their individual locations were marked. One hundred and thirty-five plants (27 beakers) were exposed to concentrations of the heavy metals; fifteen plants (three beakers) had no heavy metals added to the nutrient solutions. A set of 45 plants (nine beakers) were exposed to Pb, Zn, or Mn in solution respectively; 15 plants of each set (three beakers) were exposed to concentrations of 1 mg/L, 10 mg/L, or 20 mg/L. The nutrient solutions were changed after one week. During the experiment the solutions had a pH range of 7.8 to 9.3 and a conductivity range of 1,000 to 1,650 micromhos. Plants were illuminated for 12 hours per day at an intensity of 24  $\mu\text{E}/\text{m}^2/\text{s}$  just below the water surface. The plants were allowed to grow for two weeks, and were then weighed wet (most of the water shaken off), measured, and weighed dry (dried for two hours at 110°C).

## Storm Damage

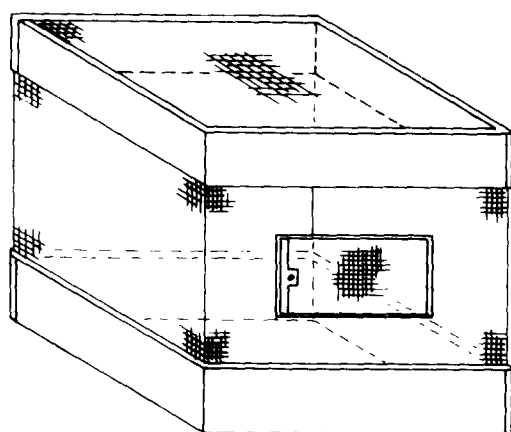
Discharge records for the tidal Potomac River at Little Falls, Maryland, were analyzed to determine whether storm damage might account for the disappearance of submersed aquatic vegetation in the tidal river. A laboratory study was conducted to look at the effects of sediment deposition on the growth of *Vallisneria*. Tubers were collected from the Port Tobacco River with a post-hole digger. Eight to 15 tubers were placed in each container and buried in sediment collected from the same site. Sediment depths ranged from 150 to 550 mm. Successful plants were those which emerged from the substrate and developed green leaves.

## Nutrients

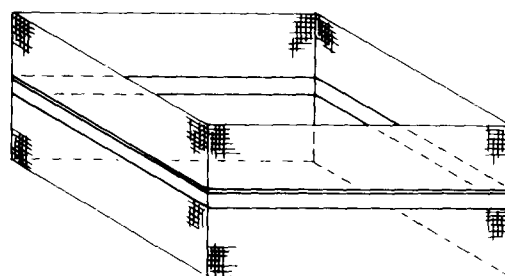
The mean and standard deviations of selected nutrient data (dissolved nitrogen and dissolved phosphorus) collected throughout the tidal river and estuary by the Potomac Estuary Study during 1979-80 (Blanchard and others, 1982) were calculated. Longitudinal distributions of dissolved nitrogen and dissolved phosphorus in the tidal river and estuary were compared to submersed aquatic vegetation biomass distribution.

## Submersed Aquatic Vegetation Transplants

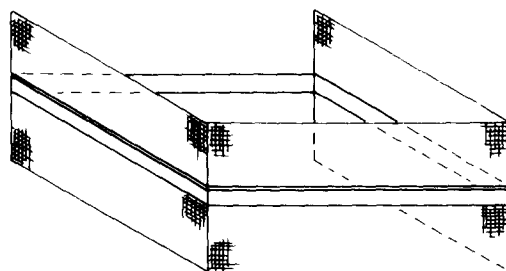
Transplant experiments were conducted in the tidal river, transition zone and estuary to assess the potential for plant survival in areas devoid of natural beds of submersed aquatic vegetation. In 1979, two rafts, each containing four large wooden boxes suspended at about 0.3 m below the water surface, were deployed in the Port Tobacco River and Piscataway Creek. Two of the boxes in each raft were filled with substrate from the site in the Port Tobacco River where the *Vallisneria* were collected and two boxes in each raft were filled with substrate taken from the Piscataway Creek area. About 50 sprigs (whole plants without soil) of *Vallisneria* were planted in each box and gravel was scattered over the top of the soil surface to prevent the soil from washing away. A third raft containing sediment from the Wicomico River transition zone was deployed in St. Clements Creek and planted with *Ruppia maritima* (widgeongrass) from the Wicomico River. Plants were checked every three to four weeks during the growing season. During 1979, sprigs of *Vallisneria* also were planted at nonvegetated open-water sites in Piscataway and Mattawoman Creeks, but



FULL ENCLOSURE WITH TOP



TOPLESS ENCLOSURE



3 - SIDED ENCLOSURE

Figure 5. Enclosures for experimental transplants of submersed aquatic vegetation in the tidal Potomac River and Estuary.

no systematic methodology was used for planting. During 1980, experimental plantings were made at nonvegetated sites at Piscataway Creek, Goose Island, Rosier Bluff, Mattawoman Creek, Elodea Cove, and Pomonkey Creek (fig. 4). In 1981, transplants were made to the four nonvegetated, transplant sites--Goose Island, Rosier Bluff, Elodea Cove, and Neabsco Bay (fig. 4). Transplant sites were selected on the basis of water depth, historical presence of submersed aquatic vegetation, substrate type, and exposure to wind and wave.

Sprigs of *Vallisneria americana*, *Potamogeton perfoliatus*, and *P. pectinatus* were removed from beds in the Port Tobacco River using a post-hole digger. Sprigs were washed to remove all sediment, placed in plastic bags with river water, and transported in coolers. Fifty to 60 sprigs of *Vallisneria* were planted by hand in the substrate to form small beds at each selected site. Plugs (blocks of substrate containing whole plants) of *Vallisneria* from the Port Tobacco River were transported in coolers and planted at the same sites (during 1981 only) by digging a shallow

trench and placing individual plugs in the trench. About 20 sprigs of *Potamogeton perfoliatus* (redhead-grass) and *P. pectinatus* were planted in a single bed at each site except Goose Island in the fall of 1981. Substrate particle size and nutrient content for transplant sites were determined (see "substrate" section). The exposure and fetch of each site were measured on U.S. Department of Commerce 1:80,000 navigation charts.

Exclosures were placed around several of the transplanted beds to test the hypothesis that grazing prevented the establishment of submersed aquatic vegetation in the tidal river. Three types of exclosures were used (fig. 5): full exclosures with a door for access; topless exclosures to see if grazers would swim or climb over the top, and 3-sided exclosures to see if predation was mostly from bottom dwellers. The area included within an exclosure was approximately 1 m<sup>2</sup>. Exclosures were constructed from 13 mm metal mesh and wood, and were held in place in the river by heavy metal fence posts. The bottom edge of the mesh extended approximately 150 mm below the surface of

the substrate to discourage burrowing grazers. One enclosure of each type was placed over sprigs at each site; only full enclosures were placed on plugs. One bed of sprigs and one of plugs was left unprotected at each site. The enclosures were destroyed by ice during the winter of 1980-81. Accordingly, the enclosures from the 1981 growing season were removed during December of 1981 and the fence posts left to mark the locations of the beds. Beds were revisited in the summer and fall of 1982 to check for regrowth.

A series of caging experiments also was conducted between 1979 and 1981. Small plastic mesh cages were constructed using a framework of fence wire and a covering of plastic mesh. These were suspended with floats at a fixed depth below the water surface. In 1979, a measured amount of *Ceratophyllum* was placed in each cage and inspected at intervals through the growing season. In 1980, 200 mm lengths of *Ceratophyllum*, *Elodea canadensis* (common elodea), and *Potamogeton crispus* were suspended in mesh cages in both the tidal river and the transition zone for three periods during the summer.

## RESULTS

### Submersed Aquatic Vegetation Survey

All field data collected during the submersed aquatic vegetation study are published in Paschal and others (1982). Results of the first 3 years of the study, 1978-81, are published in Haramis and Carter (1983).

#### Distribution

During the study, a total of 27,509 samples was collected along 256 different transects as part of the formal sampling program. Additional observations included the District of Columbia transects in 1978 and the midsummer shoreline survey in 1981. The highest frequency of occurrence of vegetated transects and the maximum number of species of submersed aquatic macrophytes were found in the transition zone of the Potomac River and the adjoining Wicomico River tributary during all sampling periods (tables 1 and 2; fig. 3). Thirteen of the 16 species recorded (11 vascular plants and 2 species of the algae *Chara*) were found in these two zones (table 3). Two of the remaining species, *Egeria densa* (water-weed) and *Najas gracillima* (naiad), were found only in the tidal river or its tributaries.

A third plant found during the shoreline survey in the tidal river in 1981 was positively identified by the

Department of Agriculture as *Hydrilla verticillata* (L.f.) Caspary (Godfrey and Wooten, 1979, p. 76). This exotic plant is considered a nuisance in Florida. The established population in the Potomac River is very small and does not appear to be a threat at this time; however, it has overwintered in the area.

Vegetation was extremely sparse in the tidal river during all sampling periods. In 1978 and 1979, only a single species, *Vallisneria*, was found on the furthest downstream transect of the Mattawoman Creek sampling region that borders the transition zone (fig. 3, table 4). During extensive informal searches for vegetation in 1980 and 1981, nine species were found, usually in very isolated or protected environments. Several small (1 m<sup>2</sup>) beds of *Vallisneria* were found on the river margin south of Alexandria, Va. and in Quantico Creek, and two larger beds were located, one on a new transect (1980) near the head of Mattawoman Creek (10 m<sup>2</sup>) and in the Washington Ship Channel near Haines Point (100 m<sup>2</sup>) (fig. 4). *Najas gracillima*, *Potamogeton pusillus*, and *Ceratophyllum* were present in the *Vallisneria* bed in Mattawoman Creek. *Egeria densa*, *Elodea canadensis*, and *Potamogeton crispus* were found in small tidal creeks and a very large population of *Zannichellia palustris* (horned pondweed) was located in the tidal pond behind National Airport. *Hydrilla verticillata* was found behind an island in Dyke Marsh, just south of Bell Haven.

In the mesohaline estuary, vegetation was most widespread in spring and least in the fall. The most widespread and abundant species were *Zannichellia* and *Ruppia*; *Zostera marina* was conspicuously absent. *Zannichellia* flowered and seeded during spring and declined in distribution and biomass thereafter, distributing seed and floating plant fragments throughout the estuary. *Ruppia* achieved little growth in this zone and plants sampled in summer of 1978, when maximum biomass occurred, were flowering, but were covered with epiphytes. Generally, large areas of the estuary were nearly devoid of aquatic macrophytes during summer and fall.

Transition-zone sampling regions along the main river contained the most extensively vegetated littoral zones in the tidal Potomac River and Estuary. *Vallisneria* and *Potamogeton perfoliatus* were the two dominant species during all sampling periods; *Zannichellia*, *Ruppia*, *Potamogeton pectinatus*, *P. crispus* and *Myriophyllum spicatum* (Eurasian watermilfoil) were found on 13 or more transects during the period of study, but were far less abundant than the two dominant species, particularly in summer and fall (tables 4 and 5). At the lower end of the transition zone adjacent to the mesohaline estuary, *Vallisneria*, *Potamogeton perfoliatus*, and *P. crispus* were found with *Zannichellia* in the Upper Machodoc Creek region in the spring

**Table 1.** Relative occurrence of vegetated transects for the Maryland regions of the tidal Potomac River and Estuary, 1978-81. [Relative occurrence as the ratio of number of vegetated transects to total number of transects; n.d. indicates no data]

Salinity zones and sampling regions	1978			1979		1980			1981		
	Spring	Summer	Fall	Spring	Fall	Spring	Summer	Fall	Spring	Summer <sup>1</sup>	Fall
<b>Tidal River:</b>											
Washington Channel WC-01R	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1/1	n.d.	1/1	n.d.	1/1
Piscataway-Mattawoman Creeks region	0/34	1/34	1/1	0/34	0/34	1/5	n.d.	n.d.	0/34	n.d.	0/34
Mattawoman MN-4T-2	n.d.	n.d.	n.d.	n.d.	n.d.	1/1	1/1	n.d.	0/1	n.d.	1/1
Pomomkey Creek	n.d.	n.d.	n.d.	n.d.	n.d.	0/4	0/4	n.d.	0/4	n.d.	0/4
<b>Transition Zone:</b>											
Maryland Point	n.d.	n.d.	n.d.	n.d.	n.d.	5/10	3/10	n.d.	3/10	n.d.	1/10
Nanjemoy Creek-Port Tobacco River region	22/37	22/37	19/37	22/37	20/37	23/37	24/37	24/37	21/37	17/17	11/37
Wicomico River region above Chaptico Bay <sup>2</sup>	5/9	2/9	2/9	7/9	2/9	7/9	4/9	2/9	6/9	2/4	0/9
<b>Estuary:</b>											
Wicomico River region below Chaptico Bay <sup>2</sup>	7/21	5/21	2/21	7/21	2/21	11/21	7/21	3/21	6/21	0/4	0/21
St. Marys River region	7/31	3/31	1/31	6/31	0/31	5/31	0/31	1/31	1/31	n.d.	0/31

<sup>1</sup> Only transects which previously had three or more species were sampled.

<sup>2</sup> The Wicomico River sampling region maintains a freshwater to saltwater gradient and thus was partitioned into transition zone and estuary.



**Table 2.** Relative occurrence of vegetated transects for the Virginia regions of the tidal Potomac River and Estuary, 1979

[Relative occurrence as the ratio of number of vegetated transects to total number of transects]

Salinity zones and sampling regions	Sampling period	
	Spring	Fall
Tidal River:		
Gunston Cove region	0/13	0/13
Transition Zone:		
Aquia and Potomac Creeks region	3/26	2/26
Upper Machodoc Creek region	12/18	9/18
Estuary:		
Nomini Bay region	8/25	1/25
Yeocomico River region	3/26	0/26

and fall of 1979. Similarly, plants were abundant in the transition zone of the Wicomico River above Chaptico Bay (fig. 6). This area was vegetated with lush growths of *Ruppia* and *Zannichellia* and was the region where *Najas guadalupensis* and the alga *Chara braunei* were most common.

A maximum number of different species (seven) occurred on only two transects; during spring of 1979, *Potamogeton crispus*, *P. pusillus* (slender pondweed), *Zannichellia*, *Ruppia*, *Vallisneria*, *Myriophyllum* and *Chara* were collected on a transect (PO-1T-5) (fig. 2) in the Port Tobacco River and *P. pusillus*, *P. perfoliatus*, *Zannichellia*, *Ruppia*, *Myriophyllum*, *Chara*, and *Najas guadalupensis* on a transect (WO-8T-1) in the Wicomico River transition zone. As many as nine different species appeared on several transition zone transects, but not simultaneously. *Najas guadalupensis*, *Elodea*, *P. pusillus* and *Ceratophyllum* were relatively rare, being found on less than eight transects over the period of study. The occurrence of species on a transect was variable from season-to-season, and from year-to-year (see examples in fig. 7). Biomass equivalents (grams dry weight per L of plant volume) are shown on table 6. Only a few samples of

**Table 3.** Species of submersed aquatic plants found in the tidal Potomac River and Estuary [Taxonomy follows Hotchkiss (1950, 1967) unless otherwise noted]

Family	Species	Common name
Characeae <sup>1</sup> (muskgrass)	<i>Chara braunii</i> Gm. <i>Chara zeylanica</i> Km. ex Wild	Muskgrass
Najadaceae (pondweed)	<i>Potamogeton perfoliatus</i> L. <i>Potamogeton pectinatus</i> L. <i>Potamogeton crispus</i> L. <i>Potamogeton pusillus</i> L. <i>Ruppia maritima</i> L. <i>Zannichellia palustris</i> L. <i>Najas guadalupensis</i> (Spreng.) Morong <i>Najas gracillima</i> Magnus <sup>3</sup>	Redhead-grass Sago pondweed Curly pondweed Slender pondweed Widgeongrass Horned pondweed Southern naiad Naiad
Hydrocharitaceae (frogbit)	<i>Vallisneria americana</i> Michx. <i>Elodea canadensis</i> (Michx.) Planch. <i>Egeria densa</i> Planch. <sup>2,3</sup> <i>Hydrilla verticillata</i> (L.f.) Caspary <sup>4</sup>	Wildcelery Common elodea Water-weed Hydrilla
Ceratophyllaceae (coontail)	<i>Ceratophyllum demersum</i> L.	Coontail
Haloragidaceae (watermilfoil)	<i>Myriophyllum spicatum</i> L.	Eurasian watermilfoil

<sup>1</sup> From Wood (1967).

<sup>2</sup> From Radford and others (1974).

<sup>3</sup> Found during shoreline survey, not on formal transects.

<sup>4</sup> From Godfrey and Wooten (1979).

*Potamogeton pusillus* were collected so the biomass equivalent was estimated to be 60 g/L for that species. The biomass per square meter in the study area was extremely variable from year-to-year and from season-to-season (figs. 6 and 8). The biomass per square meter and the total sampled biomass was highest in the transition zone and lowest in the tidal river during all years.

The number of vegetated grabs was greatest in spring of 1979 and 1980 (table 4) because many grabs

contained a trace of vegetation. Biomass, perhaps a better indicator of large viable plant populations, was highest in the summer and fall of 1978 (fig. 6 and 8). As expected, biomass is lowest in the spring and reaches its maximum in either summer or fall. Figure 9 compares the biomass and species composition for three transects that contain three or more species. Such biomass and species variability is typical of the study area.

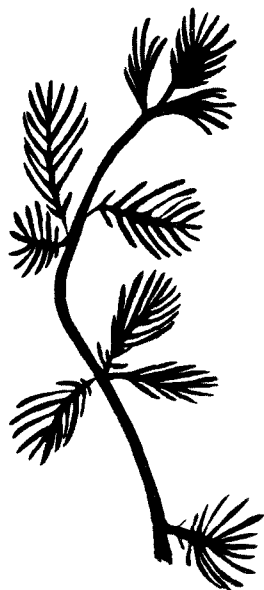
**Table 4.** Frequency of individual species in vegetated grabs in the Maryland regions of the tidal Potomac River and Estuary, 1978-81, in percentage.

For comparison, only original 1978 transects were included. This table does not include substituted or additional transects from 1980 and 1981. Because species may co-occur in some samples, the frequency column may sum to greater than 100 percent within a given zone.

Salinity zones and species	1978			1979		1980			1981		
	Spring	Summer	Fall	Spring	Fall	Spring	Summer	Fall	Spring	Summer <sup>1</sup>	Fall
Tidal River:											
<i>Vallisneria americana</i>	0	100	100	0	0	100	n.d.	n.d.	0	n.d.	0
<i>Ceratophyllum demersum</i>	0	33	0	0	0	0	n.d.	n.d.	0	n.d.	0
Total vegetated grabs	0	3	2 <sup>2</sup>	0	0	3 <sup>2</sup>	n.d.	n.d.	0	n.d.	0
Transition Zone:											
<i>Potamogeton crispus</i>	11	11	3	14	0	3	5	3	3	0	0
<i>Potamogeton pusillus</i>	0	1	0	4	0	1	2	0	0	3	0
<i>Potamogeton perfoliatus</i>	17	28	45	22	13	12	26	11	22	52	42
<i>Potamogeton pectinatus</i>	2	14	4	2	0	3	9	4	3	12	22
<i>Zannichellia palustris</i>	32	1	0	25	0	37	0	12	57	2	0
<i>Vallisneria americana</i>	37	55	75	44	63	37	61	70	31	75	40
<i>Ruppia maritima</i>	15	14	20	6	20	9	17	7	1	10	0
<i>Elodea canadensis</i>	0	0	1	1	1	0	0	0	0	0	12
<i>Ceratophyllum demersum</i>	0	2	1	6	10	5	3	3	6	6	3
<i>Myriophyllum spicatum</i>	0	4	4	6	20	3	8	19	1	0	0
<i>Chara</i> spp.	17	2	0	10	1	17	0	0	0	0	0
<i>Najas guadalupensis</i>	6	8	4	2	5	8	10	0	0	0	0
Total vegetated grabs	182	179	152	251	147	258	174	186	192	125	60
Estuary:											
<i>Potamogeton perfoliatus</i>	0	0	0	0	14	0	4	0	0	0	0
<i>Zannichellia palustris</i>	66	11	0	88	0	82	27	91	100	0	0
<i>Vallisneria americana</i>	1	0	0	0	0	0	0	0	0	0	0
<i>Ruppia maritima</i>	35	95	100	11	100	17	80	9	0	0	0
<i>Najas guadalupensis</i>	0	0	0	1	0	0	11	0	0	0	0
Total vegetated grabs	68	19	7	102	14	125	45	34	46	0	0

<sup>1</sup> Only transects that previously had three or more species were sampled.

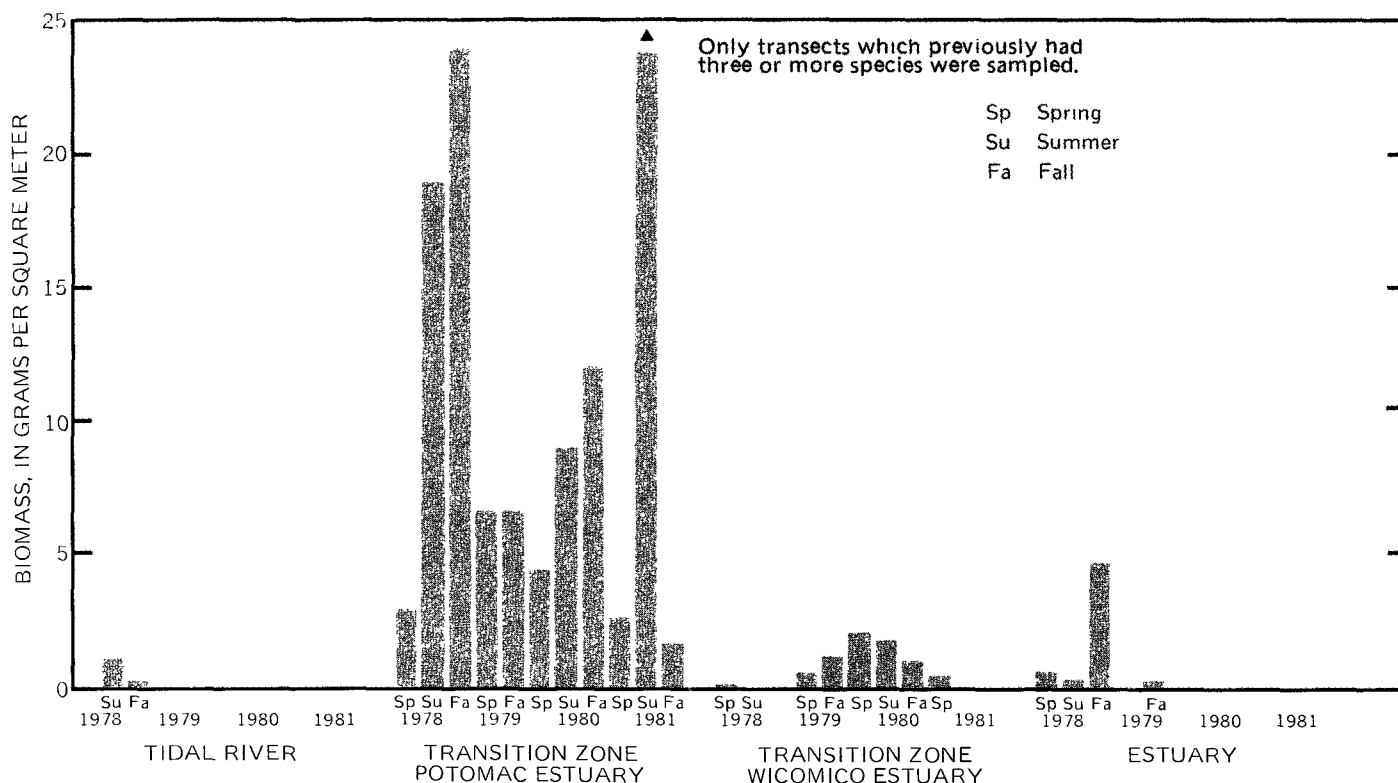
<sup>2</sup> The region was not totally resampled where there was no indication of submersed aquatic vegetation growth in previous seasons.



**Table 5.** Frequency of individual species in vegetated grabs in the Virginia regions of the tidal Potomac River and Estuary, 1979, in percentage

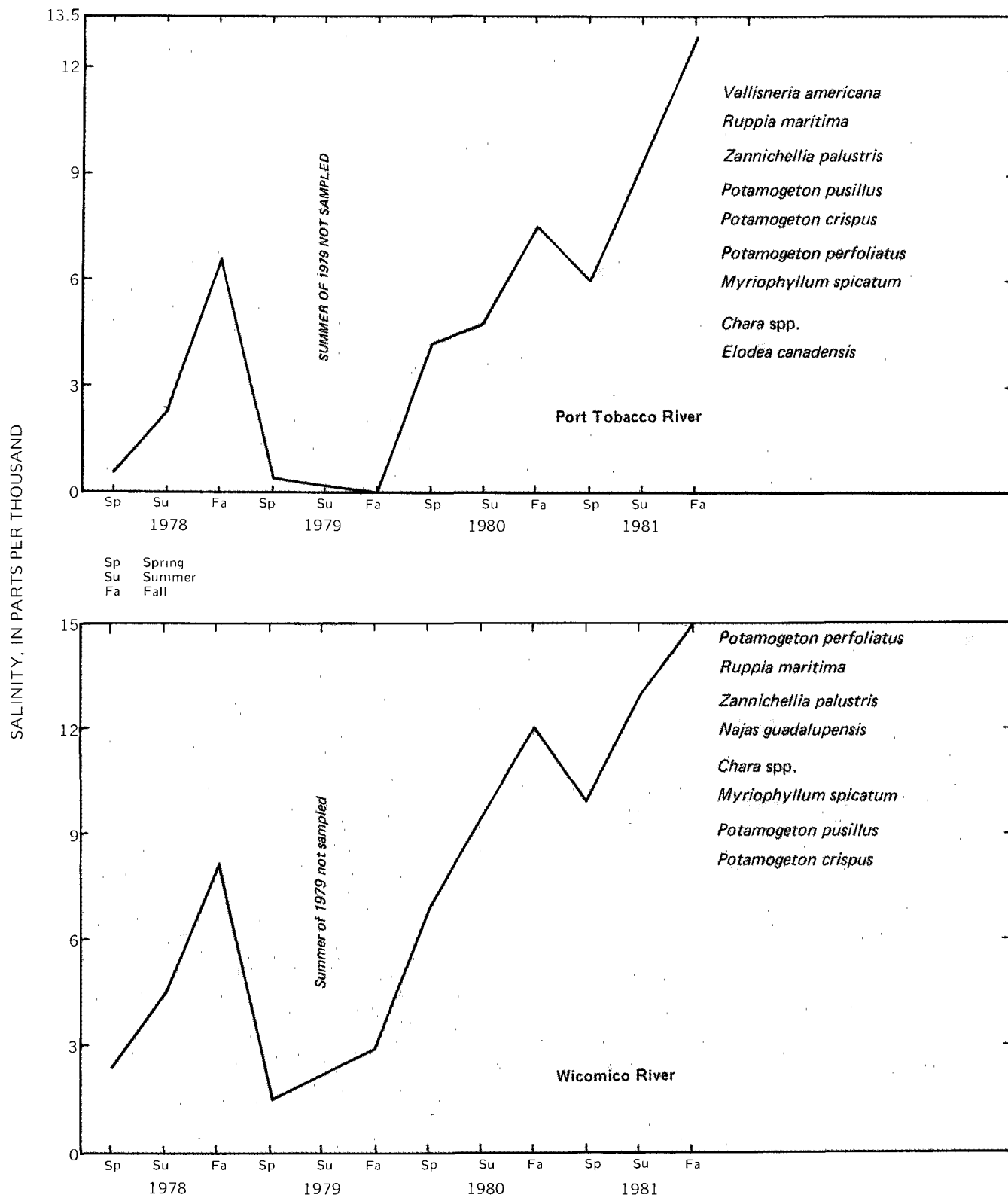
No plants were found in the tidal river. Because some samples may contain more than one species, the data may sum to greater than 100 percent within a given zone.

Salinity zones and species	Sampling period	
	Spring	Fall
Transition Zone:		
<i>Vallisneria americana</i>	48	67
<i>Potamogeton perfoliatus</i>	29	20
<i>Potamogeton crispus</i>	10	0
<i>Potamogeton pusillus</i>	7	0
<i>Zannichellia palustris</i>	7	0
<i>Potamogeton pectinatus</i>	2	0
Total vegetated grabs	89	79
Estuary:		
<i>Zannichellia palustris</i>	78	0
<i>Potamogeton pusillus</i>	22	0
<i>Elodea canadensis</i>	20	100
<i>Ruppia maritima</i>	6	0
Total vegetated grabs	50	13



**Figure 6.** Comparison of seasonal variations in biomass on Maryland transects for four salinity zones of the tidal Potomac River and Estuary, 1978-81.





**Figure 7.** Seasonal species distribution as a function of salinity for Port Tobacco River transect PO-IT-5 and Wicomico River transect WO-8T-1.

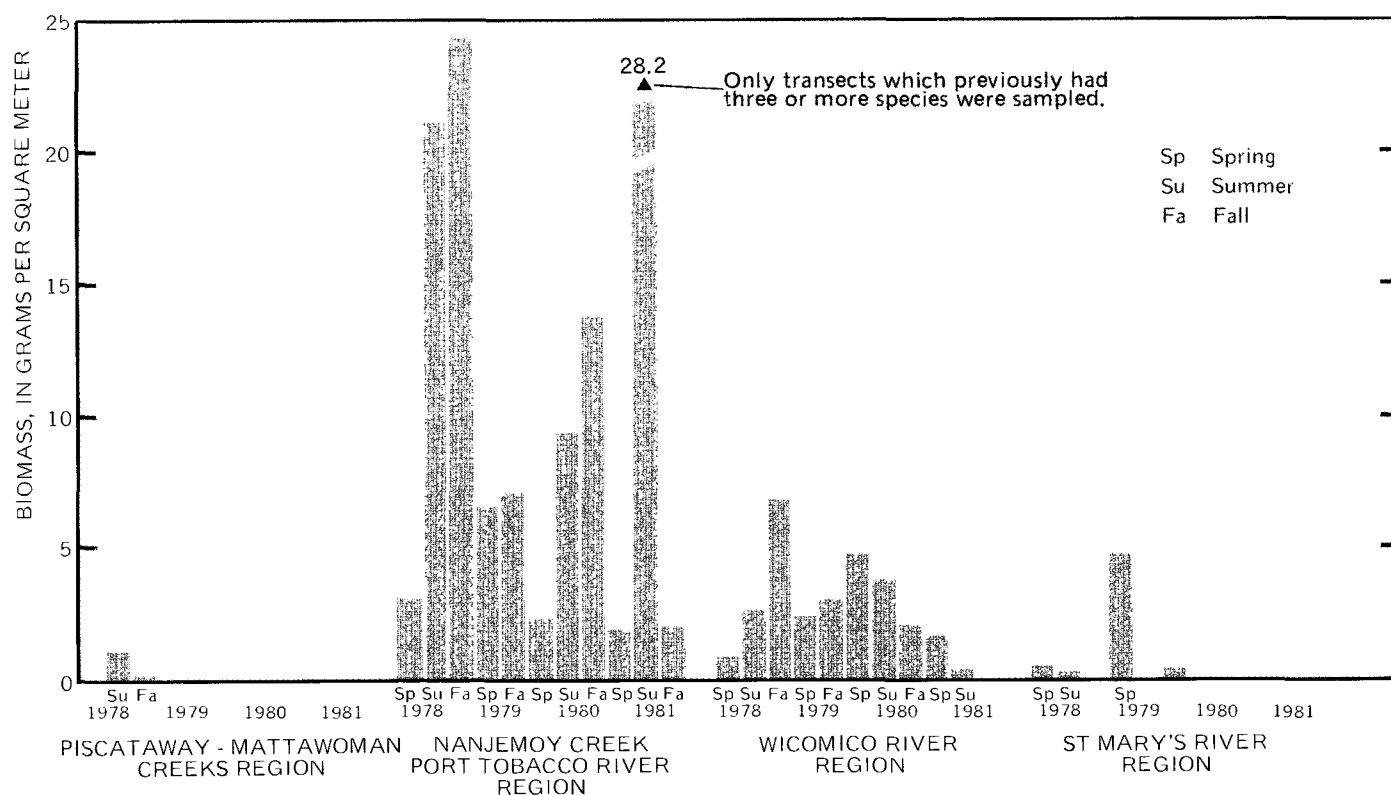
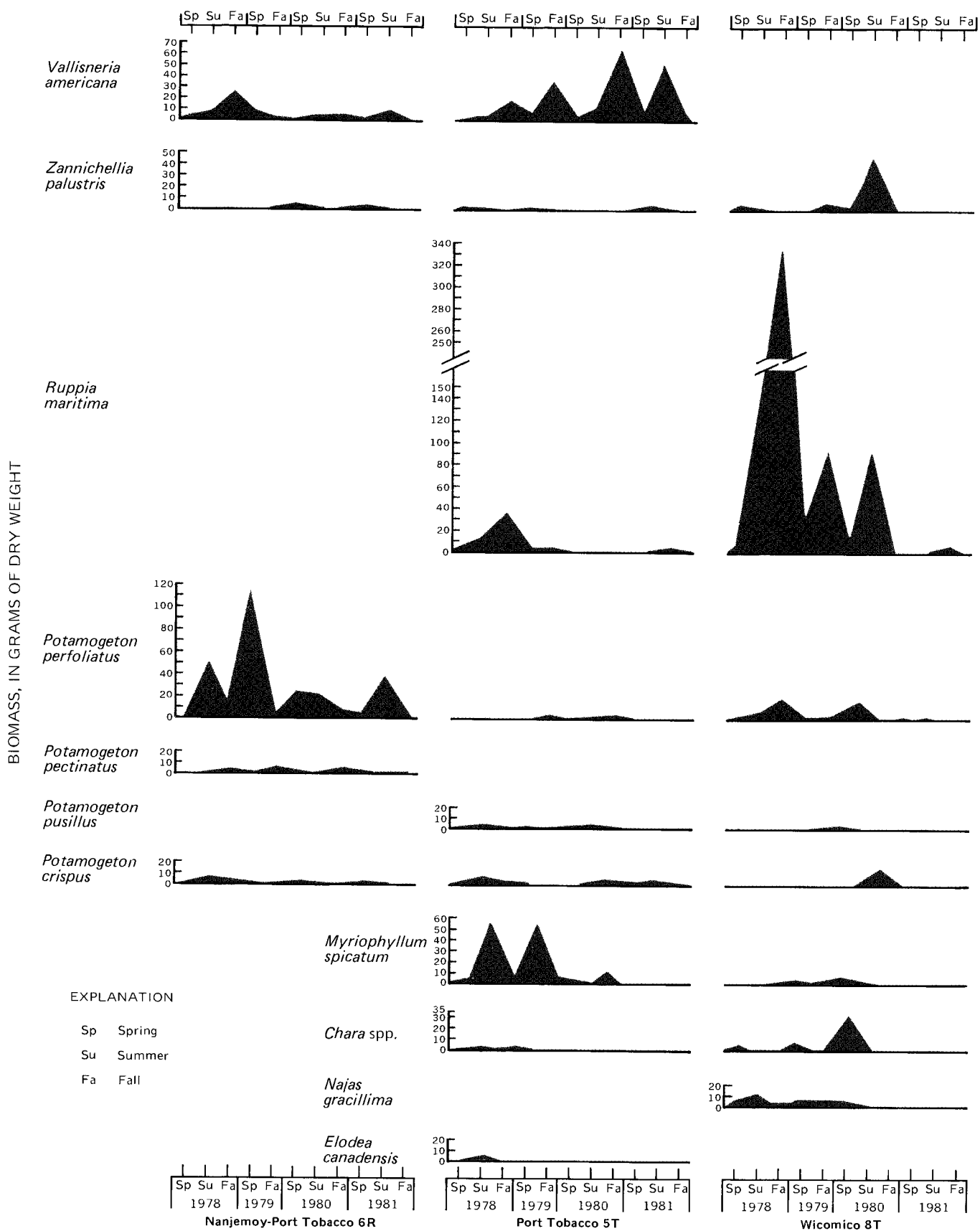


Figure 8. Comparison of seasonal variations in biomass in the Maryland regions of the tidal Potomac River and Estuary, 1978-81.

Table 6. Biomass equivalents (dry weight to volume) of submersed aquatic plants in the tidal Potomac River and Estuary, 1980, in grams per liter

Species	Number of samples	Mean biomass equivalent	95 percent confidence interval	Standard error of the mean
<i>Potamogeton perfoliatus</i> (spring)	14	80	65 - 90	6
<i>Potamogeton pectinatus</i> (spring)	12	80	73 - 97	6
<i>Potamogeton crispus</i> (spring)	9	60	57 - 73	4
(summer with winter buds)	17	120	106 - 126	5
<i>Vallisneria americana</i> (spring)	13	50	35 - 63	7
(summer)	13	90	76 - 108	7
<i>Ruppia maritima</i> (summer)	12	100	78 - 116	9
<i>Myriophyllum spicatum</i> (spring)	11	50	45 - 60	3
<i>Zannichellia palustris</i> (summer)	9	100	93 - 116	5
<i>Najas gracillima</i> (summer)	8	60	54 - 68	3
<i>Ceratophyllum demersum</i> (spring)	18	60	55 - 67	3
<i>Chara</i> spp. (summer)	10	110	95 - 129	8
<i>Elodea canadensis</i> (summer)	6	60	57 - 69	2
<i>Egeria densa</i> (summer)	11	60	48 - 79	7



**Figure 9.** Seasonal variation in biomass of individual species found on transects NP-6R (Blossom Point), PO-IT-5 and WO-8T-1 in the transition zone.

## Factors Affecting Distribution and Abundance

### Depth and Distance from Shore

Water depths at vegetated sites ranged from 0.1 to 2.0 m and averaged 0.86 m (fig. 10). Superimposing the mean tide range (U.S. Department of Commerce 1976, p. 223) for the transition-zone region along the main river on the average depth at vegetated sites reveals that most of the vegetation was in water fluctuating from about 0.6 to 1.1 m due to tide. Consistent with this relationship, we found most vegetation in near-shore zones; over 60 percent of vegetated samples were found within 60 m or less from shore (fig. 10).

### Substrate

The predominant near-shore substrate in most of the tidal Potomac River and Estuary is sand, silty-sand, or gravel. Most transects ended in silt-clay substrate when the water depth exceeded 2 m except in the estuary where long shoal areas continued to be composed of firm sand or firm sand over hard clay. Only in the protected areas in tributaries to the transition zone or estuary, or in the upper reaches of the tidal river in both tributaries and main stem, did soft silt-clay sediments occur near shore at depths less than 2 m. The sampling, therefore, is biased toward sand-based samples (fig. 11) and more vegetation was found in substrates of predominantly sand. Vegetation occurred on substrates ranging from 0 to 14 percent gravel, 10 to 95 percent sand, 4 to 62 percent silt and 2 to 39 percent clay. Nonvegetated sites ranged from 0 to 2 percent gravel, 11 to 98 percent sand, 2 to 89 percent silt and 2 to 32 percent clay.

Sixty-nine percent of the vegetated samples were on sand or silty-sand sediments and 18 percent on sandy silt-clay or silt-clay. Nonvegetated substrates were 59 percent sand or silty-sand and 28 percent sandy silt-clay and silt-clay. Other substrates shown in figure 11 include cobbles, gravel, pebbles, shells, and detritus. The proportions of substrate types were similarly distributed for depth and distance transects. Laboratory analyses of 35 soil samples collected from a variety of vegetated sediment types averaged 74 percent sand, 15 percent silt, and 11 percent clay. Only three of the laboratory samples contained less than 50 percent sand. Vegetation found on silt-clay sediments of deeper water (greater than 1.5 m) was limited to seedlings of *Ruppia* and *Zannichellia*. Silt-clay sediments supported *Myriophyllum*, *Potamogeton crispus*, *Vallisneria* and

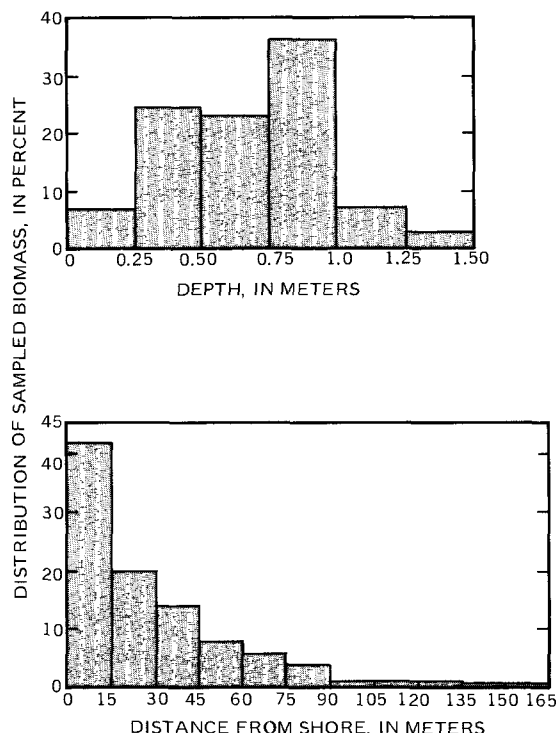
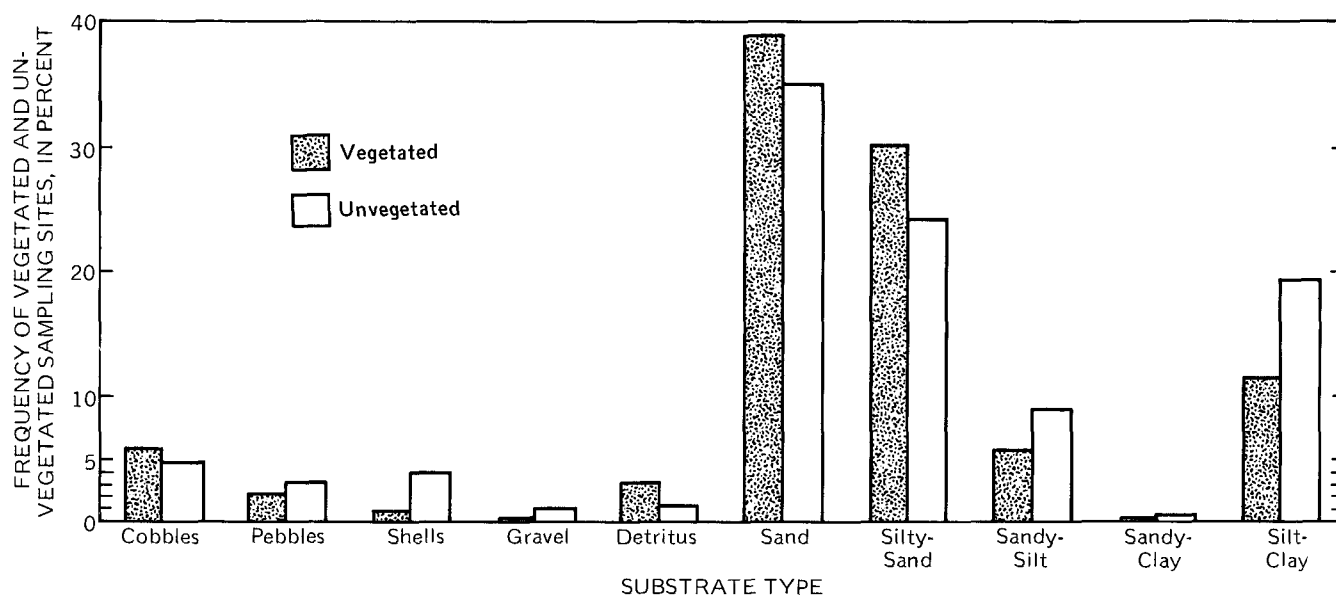


Figure 10. Distribution of sampled biomass as a function of depth and distance from shore in the tidal Potomac River and Estuary, 1978-81.

*Ceratophyllum* in shallow protected areas in the tributaries.

### Salinity, Specific Conductivity, Temperature, and pH

Table 7 summarizes the distribution of sampling regions and areas in the major salinity-related zones of the tidal Potomac River and Estuary. Table 8 shows the distribution of submersed aquatic vegetation species in relation to maximum salinity during the study period. Salinities in the transition zone regions varied from 0 to 15 ppt over the four year study, with the highest salinities occurring in the fall of 1980 and 1981. The downstream extent of species presence in the fall appears to be at least partially correlated to salinity. As salinity in the transition zone rose above 13.5 ppt, all species disappeared (fig. 7). Although increasing salinity may kill the leaves of less tolerant plants, it may not have as drastic an effect on plant tubers and seeds; good regrowth may occur in the spring when salinities are lower. *Vallisneria* can tolerate salinities up to 13.5 ppt in the transition zone. This agrees fairly well with salinity-tolerance experiments by Haller and others (1974, table 1) which demonstrated that *Vallisneria* grew at 10.0 ppt, but died and decayed at 13.3 ppt. The occurrence of high salinities in the Wicomico River transition zone (15 ppt in fall 1981) may explain why *Vallisneria* is absent from that reach. *Zannichellia* and



**Figure 11.** Frequency of sampling sites in the tidal Potomac River and Estuary with respect to substrate and presence or absence of vegetation

**Table 7.** Salinity range of salinity zones, sampling regions, and other sampling sites in the tidal Potomac River and Estuary

Sampling regions by salinity zone	Salinity range <sup>1</sup>
<b>Tidal river</b>	
Washington Channel, D.C.	Fresh
Gunston Cove, Va.	Do.
Piscataway Creek, Md.	Do.
Pomonkey Creek, Md.	Do.
Mattawoman Creek, Md.	Fresh to oligohaline
<b>Transition zone</b>	
Aquia-Potomac Creeks, Va.	Oligohaline
Maryland Point, Md.	Do.
Nanjemoy Creek-Port Tobacco River, Md.	Oligohaline to mesohaline
Upper Machodoc Creek, Va.	Do.
Wicomico River <sup>2</sup> above Chaptico Bay, Md.	Fresh to mesohaline
<b>Estuary</b>	
Yeocomico River, Va.	Mesohaline
Nomini Bay, Va.	Do.
Wicomico River <sup>2</sup> below Chaptico Bay, Md.	Do.
St. Marys River, Md.	Do.

<sup>1</sup> Follows the Venice system (Symposium on the Classification of Brackish Waters 1959): fresh = 0.5 parts per thousand, oligohaline 0.5 to 5 parts per thousand, mesohaline 5 to 18 parts per thousand.

<sup>2</sup> The Wicomico River sampling region maintains a freshwater to saltwater gradient and thus was partitioned into transition zone and estuary.

*Ruppia* are reported to be tolerant of salinities of 15 ppt (Stevenson and Confer, 1978); their disappearance from the Wicomico River in fall of 1981 most likely was caused by other factors.

There is no evidence that decreasing salinity is affecting plant distribution because all species found in the study were found in fresh water. There are no clear salinity-related plant associations as suggested by Orth and others, 1979. *Zannichellia* and *Ruppia* were closely associated in the estuary, but were also found throughout the transition zone with all other species except *Egeria densa* and *Najas gracillima*. A monospecific population of *Zannichellia* was found as far upstream as National Airport. The absence of more clearly defined plant associations may be due to the almost total lack of significant amounts of vegetation in the tidal river. Also, sheltered pools within the emergent wetlands found in the tributaries were not sampled.

Daytime water temperatures in the study area ranged from 16 to 30°C in spring, 14 to 35°C in summer, and 8 to 26.5°C in the fall. Measurements of pH made in 1978 showed a range of 6.3 to 8.6 in the Piscataway-Mattawoman Creeks region; 6.8 to 9.3 in the Nanjemoy Creek-Port Tobacco River region; 6.8 to 8.8 in the Wicomico River region; and 8.3 to 8.5 in the St. Marys River region. These pH measurements appear to be typical of many estuaries and tidal rivers and there appears to be little relationship between water temperature or pH and plant success, at least for the period of study.

### Light Penetration and Water Transparency

Differences in Secchi depth were evaluated for the tidal river, the transition zone, and the estuary. A 95-percent confidence interval was chosen for the null hypothesis of no significant difference (that is,  $P < 0.05$ ). Analysis of variance indicated that there were significant differences in transparency between zones, significant differences between seasons, and that there was a strong zone-season interaction (see table 9). However, Duncan's multiple range test (Duncan, 1951) showed that there was no significant transparency difference between the tidal river and the transition zone. The mean transparency was significantly greater in the mesohaline estuary than either of the other two zones. Duncan's test also showed that only the fall transparencies were significantly different from the other seasonal transparencies with differences being attributed to increased transparency in the estuary during the fall. Figure 12 shows the mean Secchi depths for the tidal river, transition zone and estuary.

The results of the 1981 light level (PAR) measurements (Paschal and others, 1982; Coupe and Webb,

**Table 8.** Upper limit of salinity at which individual species in the tidal Potomac River and Estuary were sampled, 1978-81

Species	Maximum salinity when sampled, in parts per thousand
<i>Egeria densa</i>	0.5
<i>Najas gracillima</i>	0.5
<i>Elodea canadensis</i>	5.0
<i>Chara</i> sp.	7.0
<i>Potamogeton pusillus</i>	7.5
<i>Ceratophyllum demersum</i>	8.5
<i>Myriophyllum spicatum</i>	10.5
<i>Najas guadalupensis</i>	10.5
<i>Potamogeton pectinatus</i>	11.0
<i>Potamogeton crispus</i>	12.0
<i>Ruppia maritima</i>	13.0
<i>Zannichellia palustris</i>	13.0
<i>Vallisneria americana</i>	13.5
<i>Potamogeton perfoliatus</i>	14.0

1983) are summarized in figure 13. The depth of deepest vegetation and the depth of greatest vegetative biomass at vegetated sites are shown on the graph. During the spring, when the plants are actively growing toward the surface, the 10 percent light depth varied between 0.5 and 1.05 m and the 1-percent light depth varied between 1.0 and 2.05 m at the intensively studied sites. One-percent light depths averaged between 1.4 and 1.6 m during the summer.

### Storm Damage

Erosion and siltation related to severe storms may wash away or bury plant beds. Four severe storms occurred during the decade of the 1930s (see table 10). In March 1936, rapid snowmelt and excessive precipitation in the Potomac and Susquehanna River watersheds caused a record 4-day high flow of 27,762 m<sup>3</sup>/s in the Potomac River near Washington, D.C. This was followed by two subsequent storms, one in April 1937, with a 3-day discharge of 20,602 m<sup>3</sup>/s, and one in October 1937 with a 3-day discharge of 11,490 m<sup>3</sup>/s. A less severe storm (3-day discharge of 10,754 m<sup>3</sup>/s) occurred in May, 1932.

Laboratory experiments showed that emergence of *Vallisneria* tubers was affected by the depth of sediment. Most of the *Vallisneria* (about 65 percent) emerged from the substrate and grew green leaves when it was covered with 150 mm of sediment, only about 25 percent emerged and grew leaves when covered with 200 mm of sediment, and none emerged when covered with 250 to 550 mm of sediment. The depth of tubers in a natural bed in the river varies from 50 to 270 mm, with most of the tubers within 150 mm of the surface.

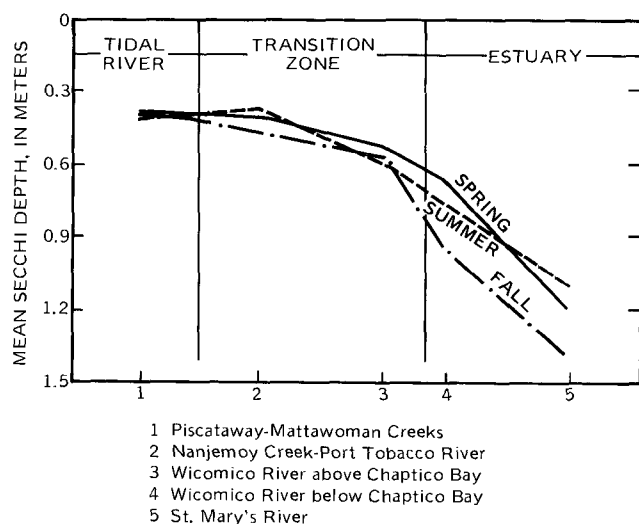
**Table 9.** Secchi-disk water-transparency measurements in major salinity zones of the tidal Potomac River and Estuary, 1978-81 [Four-year mean Secchi depth in meters  $\pm$  standard deviation; values in parentheses are number of samples]

Salinity zone <sup>1</sup> and sampling region	Spring	Season <sup>1</sup> Summer	Fall <sup>2</sup>
Tidal river			
Piscataway - Mattawoman Creeks	.50 $\pm$ .14 (84)	.47 $\pm$ .14 (25)	.39 $\pm$ .12 (48)
Transition zone <sup>3</sup>			
Nanjemoy Creek - Port Tobacco River	.44 $\pm$ .11 (98)	.42 $\pm$ .15 (34)	.49 $\pm$ .18 (72)
Wicomico River above Chaptico Bay	.52 $\pm$ .13 (35)	.59 $\pm$ .8 (13)	.57 $\pm$ .14 (23)
Mesohaline estuary <sup>2,3</sup>			
Wicomico River below Chaptico Bay	.68 $\pm$ .21 (56)	.77 $\pm$ .29 (26)	.96 $\pm$ .36 (54)
St. Marys River	1.19 $\pm$ .30 (89)	1.09 $\pm$ .33 (21)	1.38 $\pm$ .47 (58)

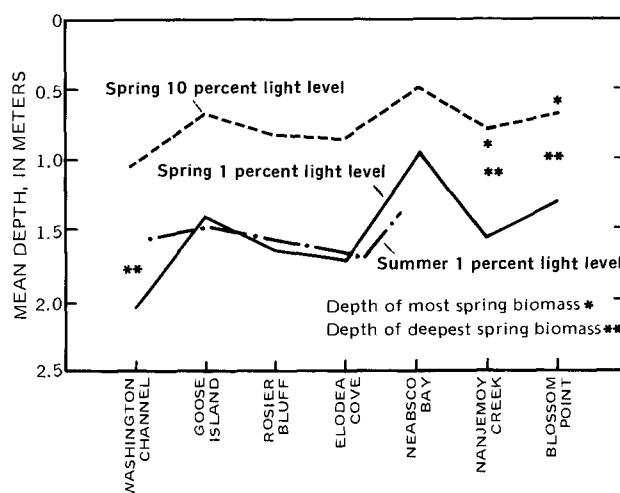
<sup>1</sup>Two-factor analysis of variance found significant seasonal differences ( $P < 0.05$ ), significant zone differences ( $P < 0.05$ ), and a strong zone-season interaction ( $P < 0.05$ ).

<sup>2</sup>Duncan's multiple range test found significantly greater mean transparency in the mesohaline estuary ( $P < 0.05$ ) and significantly different estuarine transparency in the fall period ( $P < 0.05$ ).

<sup>3</sup>Sampling region data were combined within zones before performing statistical tests.



**Figure 12.** Seasonal secchi depth in the tidal Potomac River and Estuary, 1978-81.



**Figure 13.** Light levels (photosynthetically active radiation) of one and ten percent at selected sites in the tidal Potomac River and transition zone, 1981.

## Heavy Metals

Heavy-metal accumulation in benthic soils or heavy-metal concentrations in water could inhibit plant growth, although Haslam (1978) notes that a survey conducted in Britain showed no detectable correlation of plant distribution with concentrations of any or all of ten heavy metals, even in polluted sites. Haslam pointed out, however, that the effects of heavy metals could be masked by those of other pollutants. There is ample documentation for the bioaccumulation and cycling of heavy metal by submersed aquatic vegetation (Forstner and Wittman, 1981; Peter and others, 1979; McIntosh and others, 1978; Mayes and others, 1977; Cushing and Thomas, 1980), but no evidence of toxicity effects to vascular submersed aquatic plants.

Table 11 summarizes the range of concentrations of heavy metals at vegetated and nonvegetated sites in Nanjemoy Creek. Table 12 summarizes the range of concentrations of lead, manganese and zinc in the tidal river and transition zone, 1979-81 and table 13 shows the relative loss or gain of weight of plants exposed to different concentrations of heavy metal in the laboratory experiment. No relationship between concentration of heavy metal and plant growth is indicated.

## Epiphytes

Time limitations made it impossible to run a complete epiphyte experiment in 1981. Using plastic strips for colonization, six to seven of the intensive sites and two estuary sites were sampled during the spring, but only three to five sites were sampled in the summer;

eight sites were sampled in the fall (table 14). Analysis of variance indicated that epiphyte dry weight and chlorophyll *a* biomass was significantly lower in the transition zone than in the estuary. The tidal river, like the transition zone, had relatively low epiphyte dry weight. Chlorophyll *a* biomass differed significantly among sites in the tidal river and between some of the tidal river sites and the transition zone sites. Washington Channel, Elodea Cove and Rosier Bluff had the greatest spring epiphyte chlorophyll *a* biomass--significantly higher than at the transition zone sites. Neabsco Bay and Goose Island epiphyte chlorophyll *a* were not significantly different from the transition zone. Epiphyte dry weight was significantly lower in fall, and epiphyte chlorophyll *a* biomass was significantly greater in late spring.

Light transmittance through colonized plastic strips was measured in the spring and fall. Percent transmittance is inversely related to epiphyte dry weight in the transition zone ( $r^2 = 0.67$ ), and to epiphyte dry weight and chlorophyll *a* biomass in the tidal river ( $r^2 = 0.76$  and  $0.77$  respectively); percent transmittance was not significantly (at the 5 percent level) related to either epiphyte chlorophyll *a* biomass or dry weight in the estuary. The  $r^2$  value of 0.67 indicates that 67 percent of the variance was explained by the straight line relationship. The significant (at the 5 percent level) relationships between percent transmittance and epiphyte biomass are shown in figure 14.

## Transplants

Based on 1979 box plantings, *Vallisneria* will survive on sandy substrate from Piscataway Creek or

**Table 10.** Daily discharge during storms measured at the Potomac River near Washington, D.C., in cubic meters per second (U.S. Geological Survey, 1981) [Mean annual daily discharge for site equals 311 cubic meters per second]

Day	May 1932	March 1936	April 1937	October 1937	June 1972
1	487 <sup>1</sup>	1118	283	458	203
2	1,489	948	1,426	1,370	340
3	3,255	3,679	7,075	3,679	4,868
4	4,613	12,056	8,773	4,953	7,584
5	2,887	8,362	4,754	2,858	945
6	1,588	3,396	2,434	1,356	5,660
7	1,064	2,807	n.d.	914	2,258
8	815	2,414	1,557	724	1,347
9	625	1,636	1,152	560	1,007
10	521	1,409	880	509	869

<sup>1</sup>Record starts 2 days before discharge exceeded 3,000 cubic meters per second.



Port Tobacco River equally well. However, growth at the Piscataway site was less vigorous (six plants out of 20 plants per box survived) and vegetative reproduction did not occur. Growth at the Port Tobacco site was vigorous and the plants increased from 20 per box to about 60 per box. Plant success was affected by grazing in Piscataway Creek; all the plants in one of the boxes were nipped off at the base. *Ruppia* planted in the raft in the lower Wicomico River did not survive. *Vallisneria* sprigs planted in open-water sites in 1979 and 1980 did not survive, except in 1979 at Rosier Bluff, where they were nipped off, but were still alive in the fall.

The results of the 1980 mesh-cage experiments differed from those in 1979. During 1979, *Ceratophyllum* survived at all sites, but survival was poor in Piscataway and Mattawoman Creeks and the plants were bleached out in color and covered with slime after a month of submersion. In 1980, rooted plants did poorly when segments were suspended in the river; *Ceratophyllum*, a plant with no roots, continued to be the best plant for use in this experiment. The plants in Piscataway Creek grew exceedingly well (5 to 30 times the initial length) during early summer and continued to grow well throughout the remainder of the summer and fall (table 15). The plants in Mattawoman Creek grew poorly (mean length per cage decreased) throughout the growing season. Plants in the transition zone grew well (mean length nearly doubled) during the early summer, but poorly during the rest of the summer.

The results of the transplants in enclosures during 1980 and 1981 are summarized in tables 16 and 17. Transplants in 1980 in enclosures at Rosier Bluff and Elodea Cove grew well and flowered; plants regrew

very thickly in 1981. In 1981, transplant success was excellent (plants grew well and the bed expanded) inside full enclosures at Goose Island, Rosier Bluff and Elodea Cove, fair to poor (some plants remained) inside partial enclosures, and very poor in beds with no protection. At Neabsco Bay, the only surviving plants were in poor condition in the plug bed within the full enclosure.

During 1982, all of the transplant sites were revisited several times. There was no regrowth at Goose Island. Two beds of *Vallisneria* had regrown at Rosier Bluff; one had dense growth and plants 600 mm in length and the other was quite sparse with plants less than 300 mm long. In mid-July, these plants were nipped off to about 20 mm in length; some regrowth had occurred in August and September. At Elodea Cove one small bed with plants 80 to 150 mm long was located in July, but could not be relocated in August. At Neabsco Bay, two sprigs of *Vallisneria*, 70 to 150 mm long, were found at the site in August. The natural bed at Washington Channel was flourishing, had expanded, and was flowering in mid-July. The plants were 1300 to 1600 mm in length and the Secchi depth was 1300 mm.

Cores taken with a post-hole digger from the transplant bed at Rosier Bluff (sand) were compared to cores from the natural bed at Washington Channel (sand-gravel-rock), and 2 sites in the Port Tobacco River (sand and silt-clay); one of these (silt-clay) was the site from which transplants were taken. The transplant bed had more plants in the sample (15 as compared with 2 to 6 at other sites) and the thickest rhizomes and densest rhizome mat. Plants were longest at Washington Channel (1000 mm), about 600 mm at

Table 11. Range of concentrations of heavy metals in sediments of Nanjemoy Creek 1979 [Concentrations in micrograms per gram]

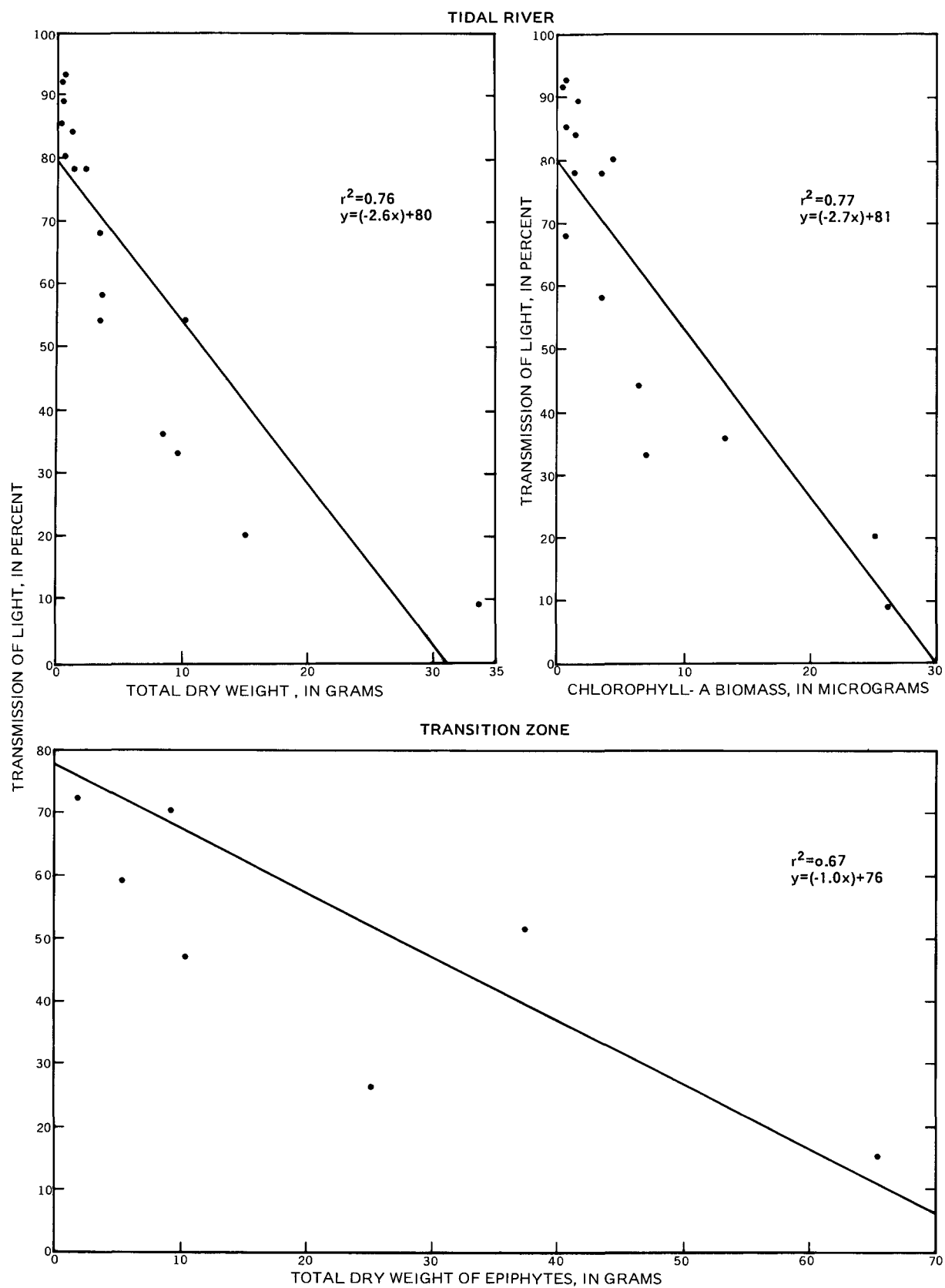
Type of site	As	Cd	Cr	Co	Cu	Fe	Pb	Mn	Hg	Se	Zn
Vegetated sites (5 sites)	0-5	10-10	10-30	10-20	10-30	3,900- 31,000	10-40	70-710	0.09- 0.66	0	20-160
Non-vegetated sites (5 sites)	0	10	10-20	10-30	10-20	1,900- 20,000	10-30	60-320	0.08- 0.31	0	10-100
Sites with $\leq 25$ percent sand (4 sites)	0-5	10-10	10-30	10-30	10-30	2,000- 31,000	10-40	120-710	0.13- 0.66	0	20-160
Sites with $> 25$ percent and $\leq 50$ percent sand (1 site)	0-2	10	10-20	20	10-20	13,000- 20,000	20	180-260	0.20- 0.32	0	60-80
Sites with $> 50$ percent and $\leq 75$ percent sand (1 site)	0	10	10	10	10	2,900- 5,700	10	90-160	0.14- 0.18	0	20-40
Sites with $> 75$ percent sand (4 sites)	0	10	10-10	10-20	10-10	1,900- 16,000	10-20	40-240	0.08- 0.23	0	10-80

**Table 12.** Concentrations of lead, manganese and zinc in tidal Potomac River and transition zone, 1979-81

Salinity zone and sampling sites	Substrate	Concentration, in micrograms per gram			Vegetation
		Lead	Manganese	Zinc	
Tidal River Sites:					
Goose Island	Silt	40	860	90	None
Piscataway Creek					
Tributary mile 1	Sand	40	410	170	Do.
Tributary mile 2	Do.	< 10	44	18	Do.
Elodea Cove	Do.	< 10	11	22	Do.
Mount Vernon	Silty-sand	20	430	76	Do.
Neabsco Bay	Sand	10	120	9-14	Do.
Mattawoman Creek					
	Do.	< 10	43	13	Do.
	Silt	40	290	59	Do.
	Sand	< 10	9	3.9	Present
Transition Zone:					
Nanjemoy Creek					
Tributary mile 4	Sand	< 10	180	55	Present
Tributary mile 1	Do.	< 10-20	290-350	97-98	None
Tributary mile 1	Silt	< 10	55-120	14-15	Present
1979 Summary (see table 11)		< 10-40	60-710	10-160	-
Port Tobacco River					
Goose Creek	Sand	< 10		48	Present
Aquia-Potomac Creek region					
Main river	Do.	10	65-90	14-20	Do.
Nanjemoy Creek-Port Tobacco River region					
Blossom Point	Do.	< 10-10	43-120	11-15	Do.
Across tributary mouth from Blossom Point.	Do.	20	550-700	150	Do.

**Table 13.** Relative growth of *Vallisneria americana* exposed to indicated concentrations of lead, manganese and zinc, 1980  
[Mean of plant weight gain (+) or loss (-) of five plants, in grams]

Sample	Control				Lead			Manganese			Zinc		
	0 mg/L	1 mg/L	10 mg/L	20 mg/L	1 mg/L	10 mg/L	20 mg/L	1 mg/L	10 mg/L	20 mg/L	1 mg/L	10 mg/L	20 mg/L
1	+0.31	+0.24	-0.03	+0.32	+0.09	+0.21	+0.18	+0.34	+0.42	+0.29			
2	+ .26	- .07	+ .39	+ .49	+ .15	+ .52	- .16	+ .42	+ .46	+ .05			
3	+ .07	- .41	+ .06	+ .17	+ .06	+ .03	- .21	+ .13	+ .23	- .04-			
Mean	+ .21	- .08	+ .14	+ .33	+ .30	+ .37	+ .10	+ .10	+ .25	- .06			



**Figure 14.** Relationship of epiphyte chlorophyll a biomass and epiphyte dry weight to transmittance of light.

**Table 14.** Epiphyte mean dry weight, chlorophyll *a*, and percent transmittance of light through epiphyte-colonized artificial substrates in the tidal Potomac River and Estuary, 1981

[Dry weight in grams per square meter; chlorophyll *a*, in micrograms per square centimeter; n.d. indicates no data]

Salinity zone and sampling site	Spring			Summer			Fall		
	Dry weight	Chlorophyll <i>a</i>	Percent transmittance	Dry weight	Chlorophyll <i>a</i>	Percent transmittance	Dry weight	Chlorophyll <i>a</i>	Percent transmittance
<b>Tidal river:</b>									
Washington Channel	6.4	6.2	44	17.2	6.6	n.d.	0.2	0.8	85
	9.9	19.7	33	3.0	4.5	n.d.	.5	1.5	89
Goose Island	3.4	1.6	54	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	3.6	3.9	58	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Rosier Bluff	34.3	26.2	9	n.d.	n.d.	n.d.	1.4	1.1	84
	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.1	1.1	78
Elodea Cove	8.3	13.1	36	n.d.	n.d.	n.d.	2.2	3.4	78
	15.0	25.2	20	n.d.	n.d.	n.d.	1.0	5.3	80
Neabsco Bay	3.4	0.8	68	n.d.	n.d.	n.d.	.8	.1	93
	10.1	1.3	54	n.d.	n.d.	n.d.	.5	.02	92
<b>Transition zone:</b>									
Blossom Point	9.1	1.8	7	44.2	3.5	n.d.	3.3	2.0	59
	10.2	3.8	47	n.d.	n.d.	n.d.	7.3	5.6	72
Nanjemoy Creek (shallow) <sup>1</sup>	65.4	2.5	15	9.9	0.5	n.d.	.1	.02	97
	n.d.	n.d.	n.d.	44.2	.2	n.d.	.1	.03	92
Nanjemoy Creek (deep)	37.4	.8	51	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	25.1	.3	26	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<b>Estuary:</b>									
Wicomico River (river)	17.8	3.0	41	57.5	8.9	n.d.	n.d.	n.d.	n.d.
	149.7	9.9	6	75.7	8.2	n.d.	n.d.	n.d.	n.d.
Wicomico River (tributary)	40.2	5.3	13	83.8	6.1	n.d.	13.7	3.7	64
	41.1	8.7	38	n.d.	n.d.	n.d.	25.2	6.6	55

<sup>1</sup> Site is 0.3 m in depth. All other sites are approximately 0.5 m deep at mean low tide.

**Table 15.** Mean lengths of *Ceratophyllum demersum* in suspended-cage experiments in the tidal Potomac River 1980 [Lengths in millimeters. Initial length of plants for each cage was 1000 millimeters]

	June 6 to July 7		July 10 to August 13		August 13 to September 12	
	Number of cages	Mean length per cage	Number of cages	Mean length per cage	Number of cages	Mean length per cage
<b>Tidal River</b>						
Piscataway Creek	24	8,450	24	2,050	24	1,120
Mattawoman Creek	30	690	36	200	30	250
<b>Transition Zone</b>						
Nanjemoy Creek	30	1,940	24	310	24	850
Port Tobacco River	30	1,840	-	-	-	-

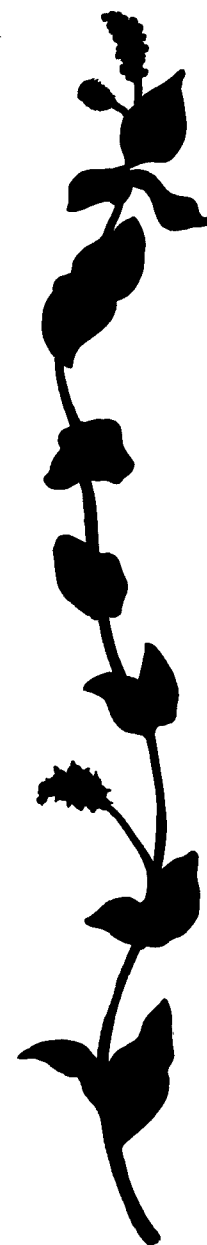
**Table 16.** Transplant survival in the tidal Potomac River, 1980-81

[E, excellent, > 100 percent, plants growing and bed enlarging; G, good, ≥ 50 percent of plants present; F, fair, < 50 percent of plants present; N, no plants]

Site	Date	Full exclosures with sprigs	No exclosures with sprigs
Goose Island	July 15, 1980	50 planted	50 planted
	July 21, 1980	F - 5 plants remain	clipped off <sup>2</sup>
	August 6, 1980	E	N
	October 14, 1980	E - dense growth	N
Rosier Bluff	July 16, 1980	62 planted	70 planted
	July 21, 1980	n.d.	clipped off <sup>2</sup>
	August 9, 1980	G - as planted	N
	October 14, 1980	E - thick growth	N
	Regrowth: <sup>1</sup>		
	July 21, 1981	E - 700 mm tall	N
	August 5, 1981	E	N
	October 9, 1981	clipped off <sup>2</sup>	N
	June 30 - September 30, 1982	E - 200-500 mm tall, clipped off <sup>2</sup> in July	N
Elodea Cove	July 28, 1980	60 planted	74 planted
	August 20, 1980	G - 45 plants remain	G - 56 plants remain
	October 14, 1980	E	E
	Regrowth: <sup>1</sup>		
	August 6, 1981	G - 40 plants remain, 500 mm tall, flowering	N
	October 9, 1981	E	N

<sup>1</sup> Regrowth not protected.

<sup>2</sup> Clipped off by grazers.



**Table 17.** Transplant survival in the tidal Potomac River 1981-82

[E, excellent, > 100 percent, plants growing and bed enlarging; G, good,  $\geq$  50 percent of plants present; F, fair, < 50 percent of plants present; N, no plants]

Site	Date	Full exclosures with plugs	Full exclosures with sprigs	Topless exclosures with sprigs	Three-sided exclosures with sprigs	No exclosures with plugs	No exclosures with sprigs
Goose Island	May 12, 1981	50 to 100 plants and tubers planted	-	-	-	50 to 100 plants and tubers planted	-
	June 16, 1981	E - plants tall	50 planted	50 planted	50 planted	G - plants short	50 planted
	July 21, 1981	E - 1 m tall	E - 1 m tall	F - 0.2 m tall	F - 0.2 m tall	N	N
	August 9, 1981	E - flowering, 0.4 m tall	E - 0.4 m tall	clipped off, <sup>1</sup> 1 cm tall	clipped off, <sup>1</sup> 1 cm tall	N	N
	October 9, 1981	G - 25 plants remain, 0.3 m tall	G - 38 plants remain, 30 cm tall	F - 0.05- 0.10 m tall	N	N	N
Rosier Bluff	May 1, 1981	50 to 100 plants and tubers planted	-	-	-	50 to 100 plants and tubers planted	-
	June 16, 1981	E - plants tall	50 planted	50 planted	50 planted	G - plants short	50 planted
	July 21, 1981	E - bed enlarging beyond exclosure, 0.6 m tall	E - 0.45 m tall	E - 0.55 m tall	F - 0.32 m tall	F - 0.25 m tall	F - 0.35 m tall
	August 5, 1981	E - bed enlarging beyond exclosure	E - bed enlarging beyond exclosure	G	G	G	G
	October 9, 1981	clipped off, <sup>1</sup> cage door open	E - as before	clipped <sup>1</sup> off	clipped <sup>1</sup> off	clipped <sup>1</sup> off	clipped <sup>1</sup> off

<sup>1</sup> Clipped off by grazers.

<sup>2</sup> Planted in 1980, regrowth not protected.

**Table 17.** Transplant survival in the tidal Potomac River 1981-82--Continued

[E, excellent, > 100 percent, plants growing and bed enlarging; G, good,  $\geq 50$  percent of plants present; F, fair, < 50 percent of plants present; N, no plants]

Site	Date	Full exclosures with plugs	Full exclosures with sprigs	Topless exclosures with sprigs	Three-sided exclosures with sprigs	No exclosures with plugs	No exclosures with sprigs
Regrowth 1982 <sup>2</sup>							
Rosier Bluff	June 30, 1982	N	G - 0.3 m tall, bed small	N	N	N	N
Rosier Bluff	July 21, 1982	N	clipped off, <sup>1</sup> 0.02 m tall, dense rhizome network	N	N	N	N
	August 17, 1982	N	G - 0.05 m tall, bed 0.3 m <sup>2</sup> , dense rhizome mat	N	N	N	N
	September 17, 1982	N	G - 0.2 m tall, bed 0.3 m <sup>2</sup>	N	N	N	N
	September 30, 1982	N	clipped off, <sup>1</sup> 0.02 m	N	N	N	N
6							
Elodea Cove	May 1, 1981	50 to 100 plants and tubers planted	tall, bed 0.9 m <sup>2</sup>	-	-	50 to 100 plants and tubers planted	-
	June 16, 1981	E - plants tall	50 planted	50 planted	50 planted	G - plants short	50 planted
	July 21, 1981	E - 1 m tall	E - 0.9 m tall	G - 0.2 m tall	F - 0.05 m tall	F - 0.1 m tall	N
	August 6, 1981	E - bed enlarging beyond exclosure, flowering	E - bed enlarging beyond exclosure, flowering	G - 0.5 m tall, flowering	-	F - 0.5 m tall	F - 0.3 m tall

<sup>1</sup> Clipped off by grazers.

<sup>2</sup> Planted in 1980, regrowth not protected.

**Table 17.** Transplant survival in the tidal Potomac River 1981-82--Continued

[E. excellent, > 100 percent, plants growing and bed enlarging; G. good,  $\geq$  50 percent of plants present; F. fair, < 50 percent of plants present; N. no plants]

Site	Date	Full exclosures with plugs	Full exclosures with sprigs	Topless exclosures with sprigs	Three-sided exclosures with sprigs	No exclosures with plugs	No exclosures with sprigs
Elodea Cove	October 9, 1981	E - bed enlarging beyond exclosure, door ajar	E - bed enlarging beyond exclosure, door ajar	E - bed enlarging beyond exclosure 0.16 m tall	E - bed enlarging beyond exclosure, 0.16 m tall	F	N
	Regrowth 1982 <sup>2</sup>						
	July 20, 1982	G - bed 0.9 m <sup>2</sup> , 0.15 m tall	N	N	N	N	N
	August 17, 1982	N	N	N	N	N	N
Neabsco Bay	May 31, 1981	50 to 100 plants and tubers planted	-	-	-	50 to 100 plants and tubers planted	
	June 16, 1981	G	50 planted	50 planted	50 planted	G	50 planted
	July 14, 1981	G - 0.6 m tall, coated with epiphytes	F - 20 plants remain, 0.2 m tall	G - 0.6 m tall, coated with epiphytes	N	F - 20 plants lying down, unhealthy in appear- ance, 0.3 m tall	N
	August 25, 1981	F - plants lying down, unhealthy in appear- ance, 0.2 m tall	F - plants lying down, unhealthy in appear- ance, 0.3 m tall	F - plants lying down, unhealthy in appear- ance, 0.2-0.5 m tall	N	N	N
	October 21, 1981	F - plants short, unhealthy in appear- ance	N	N	N	N	N
	Regrowth 1982 <sup>2</sup>						
	August 17, 1982	F - 2 plants, 0.15 m tall	N	N	N	N	N
	September 17, 1982	N	N	N	N	N	N

<sup>1</sup> Clipped off by grazers.

<sup>2</sup> Planted in 1980, regrowth not protected.



Rosier Bluff and at the silt-clay site in Port Tobacco, and shorter at the remaining site.

The characteristics of the intensively studied sites, 4 transplant sites and 3 vegetated comparison sites, are shown on tables 18 and 19. There are some large differences between the site characteristics; the exposures and fetches are quite variable, even on the vegetated sites. Rosier Bluff, Elodea Cove, Blossom Pt., and Neabsco Bay have sandy substrates, whereas Nanjemoy Creek and Goose Island have silty substrates. Washington Channel is predominantly sand and gravel but has a high percentage of silt. Goose Island, adjacent to the Blue Plains Sewage Treatment Plant, has high carbon and heavy-metal concentrations in the sediment compared with other measured sites. Nitrogen concentrations are high at Washington Channel, Goose Island, and Nanjemoy Creek--the sites with considerable silt. High nitrogen concentrations at Elodea Cove and Nanjemoy Creek probably reflect the presence of much marsh detritus (leaves, stems) in the sediments. Phosphorus concentrations are very similar at all sites; however, they are lowest in the sand substrates at Rosier Bluff and Blossom Point.

Comparison of the sediments of the intensively studied sites with those at other sites showed the following similarities and differences. High concentration of carbon at Goose Island (28 g/kg) was exceeded at two sites in the nonvegetated reach of Mattawoman Creek (55 and 59 g/kg), but was similar to carbon concentrations in a silty nonvegetated substrate at Mt. Vernon and on a sandy, vegetated site in Mattawoman Creek. Nitrogen concentrations were generally highest in substrates high in silt and lowest in sand substrates, except for nitrate plus nitrite concentrations which were very similar except for Nanjemoy Creek. Phosphorus concentrations were lower in sandy substrates than in silty-sand or predominantly silt substrates. Plants grew on sites irrespective of nitrogen and phosphorus concentrations. *Vallisneria* grew on all vegetated sites sampled except the Nanjemoy Creek intensively studied site where *Ceratophyllum*, *Myriophyllum* and *Potamogeton crispus* grew in the silt-clay substrate.

## DISCUSSION

### Factors Influencing Distribution and Abundance

The present distribution and abundance of submersed aquatic vegetation in the tidal Potomac River and Estuary differs from the historical distribution and abundance; the transition zone is the primary locus for the remaining submersed aquatic vegetation, whereas,

vegetation was also abundant in the tidal river and estuary in the early 1900's. This study has concentrated on the tidal river and transition zone, leaving the explanation for the disappearance of *Zostera marina* in the estuary to other scientists concerned with this problem (Orth and others, 1979, 1982).

Many factors, both natural and man-related, have been implicated in the decline of submersed aquatic vegetation populations in the Chesapeake Bay and other aquatic ecosystems. (Stevenson and Confer, 1978; Stevenson and others, 1979; Mills and others, 1966; Phillips and others, 1978; Haslam, 1978; Orth and others, 1982). Isolation of the factors responsible for the decline of plants is difficult because of the presence and interaction of multiple factors. In this study, multiple hypotheses were developed and field or laboratory experiments were then designed to isolate single parameters or closely related factors. Some factors were then eliminated from further consideration although synergistic effects may exist.

The factors most likely to be responsible for the present submersed aquatic vegetation distribution in the tidal river and transition zone appear to be storm damage, light, nutrient enrichment, and grazing pressure. Substrate, ecological tolerance, and salinity dynamics in the transition zone also may play important roles. Temperature and salinity play a role in determining plant distribution, phenology, and abundance, but they are only partially responsible for the present distribution of submersed aquatic vegetation. Based on the results of our study and a survey of the literature, pH, petrochemicals, heavy metals, herbicides (Kemp and others, 1982), high chlorine concentrations or disease do not appear to be the primary causes of the present submersed aquatic vegetation distribution in the tidal river and transition zone. Many of our conclusions are similar to those reached in the recent Environmental Protection Agency studies on submersed aquatic vegetation in the Chesapeake Bay (U.S. Environmental Protection Agency, 1982).

### Storm Damage

Severe storms can cause extensive damage to submersed aquatic plant populations (Bayley and others, 1978; Haslam, 1978) and storms are often responsible for the cyclic growth of plant populations (Haslam, 1978). Erosion may remove plants, especially those established where silt and sand have accumulated during low or normal flows. Increased turbidity, scouring action and deposition may change the light conditions and the composition of the bottom sediments and may smother the plant beds. According to the Chesapeake Research Consortium (1976), the impact of Hurricane

**Table 18.** Characteristics of intensively studied sites in the tidal river and transition zone, 1978-81

[Fetch in kilometers; salinity in parts per thousand; gravel, greater than 2 mm; sand, less than 2 mm and greater than 0.062 mm; silt, less than 0.062 mm and greater than 0.004 mm; clay less than 0.004 mm]

Site	River <sup>1</sup> kilometer	Vegetated	Fetch	Exposure	Description	Particle-size distribution, in percent				
						Salinity	gravel	sand	silt	clay
Tidal River:										
Washington Channel	181	yes	3.4	southwest and south	protected - in a narrow channel behind Haines Pt.	.5	10.2	37.6	34.5	17.7
Goose Island	172	no	12.0	west, north and south	exposed - beside a small island in the main channel of the Potomac River	.5	0 0	42.2 14.7	57.8 66.8	0 18.5 <sup>2</sup>
Rosier Bluff	166	no	7.4	northwest	exposed - off a sandy, high energy beach on the main stem of the Potomac River	.5	0	93.9	3.8	2.3
Elodea Cove	154	no	2.6	north	protected - in a small cove on the main stem of the Potomac River	.5	0 0	96.2 80.8	3.8 14.3	0 5.0 <sup>2</sup>
Neabsco Bay	135	no	13.5	northeast	protected, except from the north-west- in a large cove at the mouth of Occoquan Bay	0-1.0	1.8	65.2	23.3	11.5
Transition Zone:										
Nanjemoy Creek	6	yes	2.6	southeast	protected - in a narrow fork of Nanjemoy Creek	0-8.5	0 0	18.9 27.1	42.5 41.8	38.6 31.1
Blossom Point	94	yes	12.4	southwest	exposed - off a point at the mouth of Nanjemoy Creek	0-8.5	0 0	94.9 92.8	0.4 4.3	4.6 2.9

<sup>1</sup> River kilometers in distance from the mouth of the Potomac River.

<sup>2</sup> Two sets of measurements were made.



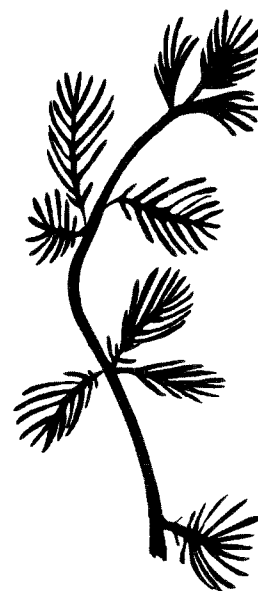
**Table 19.** Sediment characteristics of intensively studied sites in the tidal Potomac River and transition zone, 1978-81

[Nutrient concentration ranges and means (in parentheses) in milligrams per kilogram; carbon concentrations in grams per kilogram; heavy metal concentrations, in micrograms per gram; n.d. indicates no data]

NUTRIENT CONCENTRATIONS							
Site	Total as N	Ammonia plus organic as N	Nitrite plus nitrate as N	Ammonia as N	Nitrite as N	Phosphorus as P	Total Phosphorus
Washington Channel	672-1,910 (1,140)	670-1,900 (1,140)	2.0-5.7 (3.4)	23-41 (29)	0.4-0.6 (0.5)	150-220 (180)	n.d.
Goose Island	802-3,300 (2,200)	800-3,300 (2,130)	1.9-3.2 (2.7)	31-45 (37)	.4-.6 (0.5)	260-470 (370)	440
Rosier Bluff	443-734 (593)	440-730 (590)	2.2-3.7 (2.9)	4.3-11 (7)	.4 (.4)	110-140 (127)	n.d.
Elodea Cove	662-1,400 (3,000)	660-1,400 (1,050)	1.8-2.3 (2.0)	22-26 (24)	.4-.5 (.5)	180-340 (270)	220-260
Neabsco Bay	191-280 (224)	190-280 (220)	1.2-12 (6.6)	13-54 (58)	0 (0)	200-420 (270)	n.d.
Nanjemoy Creek	14,500-23,000 (18,100)	14,500-23,000 (18,070)	5.8-9.9 (7.3)	85-219 (160)	.4-2.6 (1.7)	240-420 (353)	n.d.
Blossom Point	483-852 (654)	480-850 (650)	1.7-16 (6.8)	7.2-11 (8.8)	.4-.5 (.4)	88-170 (120)	n.d.

CARBON CONCENTRATIONS				HEAVY METAL CONCENTRATIONS		
Site	Inorganic carbon	Organic carbon	Total carbon	Pb	Mn	Zn
Washington Channel	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Goose Island	1.5	15	16	40	860	90
Rosier Bluff	0	1.4	1.4	n.d.	n.d.	n.d.
Elodea Cove	0	4.3	4.3	10	11	22
Neabsco Bay	0	0-2.5	0-2.5	10	120	12
Nanjemoy Creek	n.d.	n.d.	n.d.	35	545	135
Blossom Point	n.d.	n.d.	n.d.	10	81	17



Agnes on the upper Chesapeake Bay was mostly depositional. The Susquehanna Flats, heavily colonized by submersed aquatic vegetation, received 150 to 250 mm of sediment. Following the storm, populations of *Vallisneria americana*, *Najas* sp., and *Elodea canadensis* fell to zero in previously vegetated areas and there was no recovery by 1975. *Myriophyllum spicatum* and *Heteranthera dubia* were the only submersed aquatic plants found on the flats during 1972-75 (Bayley and others, 1978, table 1) and their abundance was rated as rare or very rare. These results are similar to the results of our sedimentation experiment which showed that tubers of *Vallisneria* did not emerge when they were covered with sediments 200 to 550 mm deep. Although it is not possible to estimate the amount of scour or deposition caused by the 1930 storms, it is interesting that Hirschberg and Schubel (1979) found sediment deposition of more than 200 mm in the upper Chesapeake Bay which they attributed to the severe storm of 1936.

Haslam (1978) discusses storm damage to submersed aquatic plants at great length. Frequency and intensity of storms are important because plant tolerance is dictated by regrowth potential in the interval between storms. After exceptionally severe storms, years or decades may be required for recovery (Haslam, 1978). High discharges lasting several days are more damaging than short ones, and, given equal discharge, storms in which the discharge increases very rapidly are more damaging than those where the discharge increases more slowly. Severe erosion removes roots, tubers and rhizomes as well as shoots. Stormflows in the winter and spring cause the most erosion because there is no vegetative cover to protect the soil; plant roots and rhizomes do not form a strong anchoring mat until later in the growing season (Haslam, 1978). Seasonal dieback of submersed aquatic vegetation generally occurs between September and December, and, although stormflows late in the summer may cause damage and lower biomass, submersed aquatic vegetation usually has enough food stored to begin growth the following year. However, damage at the end of the annual growth period may lower biomass leaving the stands sparse and susceptible to damage from later storms. Storm damage occurring several years in a row may lead to a decrease in or total loss of plant populations.

It is possible that the effects of the three major storms that occurred within a 19-month period (March 1936 to October 1937) could have totally devastated the submersed aquatic vegetation in the reach below Washington, D.C., by covering the beds with sediment before the growing season or by scouring the bottom and carrying away roots, rhizomes, seeds, and winter buds. The March 1936 storm had the most rapid rise in

discharge and the highest discharge, and occurred when the plant beds were most vulnerable to erosion. Assuming damage was heavy, but that pockets of plants survived, the subsequent storms of April, 1937, and October, 1937, could have removed any regrowth. The October 1937 storm, hitting an already weakened population at the end of the growing season, could have eliminated most of the submersed aquatic vegetation in the tidal river except for pockets too small to provide sufficient material for revegetation.

### Light and Nutrient Enrichment

The maximum depth to which submersed aquatic plants can grow is highly dependent on light penetration, although other factors also play a role in determining the extent of zonation, at least in lakes (Hutchinson, 1975). In Trout Lake, Wisconsin, for example, most of the submersed aquatic plants are found no deeper than the 3-percent (percent of incident light) light depth, and none go as deep as the 1-percent light depth (Hutchinson, 1975; p. 417). These plants include 4 species found in the Potomac: (1) *Potamogeton pectinatus*, found at the 14-percent light depth; (2) *Elodea canadensis*, at the 4.5 percent light depth; (3) *Vallisneria americana*, at the 4.5-percent light depth; and (4) *Ceratophyllum demersum*, at the 1.8-percent light depth.

Titus and Adams (1979) studied the coexistence and comparative light relations of *Myriophyllum spicatum* and *Vallisneria americana* in two Wisconsin lakes. They found that, for the midsummer growth form at a rooting depth of 800 to 900 mm, *M. spicatum* had 68 percent of its shoot biomass within 300 mm of the surface whereas *V. americana* had 62 percent of its shoot biomass within 300 mm of the bottom. The light extinction coefficient for *Vallisneria* ranged from 0.013 to 0.019 m<sup>2</sup>/g, much higher than that of *M. spicatum* (0.006 m<sup>2</sup>/g). There is less effective penetration of light to lower leaves of *V. americana*, but *V. americana* was shown to have a far better physiological adaptability to low light regimes and thus compensated, at least in midsummer, for apparently disadvantageous morphological features. *Vallisneria* acclimates very rapidly to increasing light; initial light saturation at 140  $\mu$ E/m<sup>2</sup>/s and an apparent high light inhibition of photosynthesis similar to a typical "shade" plant changed to a photosynthetic rate very similar to *M. spicatum* within 24 hours of exposure to high light. The choice of *Vallisneria* for transplants, although partially dictated by the presence of large source beds and ease of transplanting, provided a species that could succeed under all but the most adverse conditions and that grew well historically in the tidal river.

Reduced light penetration has often been cited as a major cause for submersed aquatic vegetation decline in the Chesapeake Bay area and the Potomac River. For example, Martin and Uhler (1939, p. 120) and Slavik and Uhler (1951) cited the loss of aquatic plants in the Potomac River as a result of increased turbidities due to water containing suspended silts and clays. Cumming and others (1916) emphasized the effects of the vegetated flats in the fresh-water tidal Potomac River on reducing turbidity in the river. They found high turbidities on the flats during the winter and spring when vegetation was absent, but in spite of this turbidity, the vegetation grew some 1.2 to 1.5 m to the surface and the water on the flats was generally clear in summer and fall. The presence of large plant beds serves to reduce turbidity and increase water transparency (Boynton and Heck, 1982). The Secretary of the Treasury (1933) discussed in detail the baffling and mixing effect of the dense growth plants on the sewage effluent from Alexandria and the rapid decomposition of organic material in the water containing plant-derived oxygen. He also points out that dredging for sand and gravel on Oxon Flat (fig. 1) was causing high turbidity and a build-up of silt on adjacent plants. Filling in the Hunting Creek Flat (fig. 1) had eliminated about 3 percent of the area previously covered by plants. Plant growth under conditions of high turbidity and low light penetration is confined to shallower water, decreasing the total amount of vegetation present and eliminating the most light sensitive species.

Reduced light penetration is caused by increased turbidity from large algal concentrations as well as by suspended sediment. In lakes, tidal rivers and estuaries, depth of the euphotic zone (1-percent light penetration) varies with phytoplankton density; in some lakes (Spence, 1976) the phytoplankton density is large enough and variable enough to upset any direct relationship between the zone colonized by macrophytes and the euphotic zone. Spence (1976) states that macrophyte growth and performance (biomass) should not be predictable in a straightforward fashion in overenriched waters; this was the case in the Potomac River.

An increase in algal concentrations in the tidal river may be associated with the long term increase in nutrient enrichment from the Potomac River watershed and the Washington Metropolitan area. In 1971, Jaworski and others reported that about 14.2 m<sup>3</sup>/s of sewage discharge enter the tidal river, contributing 1.1 metric tons/d of ultimate oxygen demand, 204 metric tons/d of phosphorus, and 27.2 metric tons/d of nitrogen. This is in contrast to loadings of about 2.3 metric tons/d of phosphorus and 3.4 metric tons/d of nitrogen during the decade between 1910 and 1920. Recently, Steenis (1971, p. 26) stated that sewage effluent was

the main cause for increased blooms of green and blue-green algae, which have increased turbidity and promoted progressive loss of seed-bearing plants in a some 64-km reach below Washington since 1930. Nutrient enrichment has prompted blooms of the nuisance blue-green algae *Anacystis*, which has been persistent in the tidal river since the early 1960's, often forming green mats of cells at the water's surface (Jaworski and others, 1971; Pfeiffer and others, 1972). Such blue-green algal blooms are particularly severe during summer low-flow periods, during which high temperatures, low flushing rates, and high nutrient availability combine to promote growth.

The introduction of sewage wastes and nutrients from non-point sources may have changed the balance between phytoplankton and macrophyte growth and favored a major ecological shift in primary productivity. The literature contains much information that supports the competitive relationship between macrophytes and phytoplankton in enriched waters (Spence, 1976; Jupp and Spence, 1977a, 1977b; Moss, 1976; Mulligan and Baranowski, 1969; Morgan, 1970; Goulder, 1969; and others). Recently Phillips and others (1978) have reviewed this relationship and have presented evidence for a complex interaction between macrophytes, epiphytes, and phytoplankton (fig. 15). They acknowledge the ability of certain macrophytes to secrete phytoplankton suppressants, and identify heavy epiphyte and filamentous algal growth as the causative agents of initial macrophyte decline under enriched conditions. Following this initial decline, shading from increased phytoplankton populations can eliminate the remaining vegetation. Experiments with the fertilization of fishponds document the elimination of macrophytes in this way (Smith and Swingle, 1941). The Secretary of the Treasury (1933) reported that there was an increase in the blue-green algal populations on the flats near Alexandria, probably as a result of increased sewage discharge. The macrophyte-epiphyte-phytoplankton balance may already have begun to shift at that time.

Although the analyses of Secchi-depth transparencies showed no significant differences between the tidal river and the transition zone for the period 1978 to 1982, the measurements of photosynthetically active radiation (PAR) (fig. 14) suggested that there are local differences in light penetration at the transplant and naturally vegetated intensively studied sites. Secchi depths also varied among intensive sites. The sites can be ranked seasonally from highest average Secchi depth or 1-percent PAR (level 1) to lowest average Secchi depth or 1-percent PAR (level 7) as follows:

	Spring	Secchi Summer	Fall	PAR Spring
Washington Channel	1	1	-	1
Elodea Cove	2	2	2	2
Rosier Bluff	3	3	1	3
Goose Island	4	4	-	5
Nanjemoy Creek	5	7	3	4
Neabsco Bay	6	5	5	7
Blossom Point	7	6	4	6

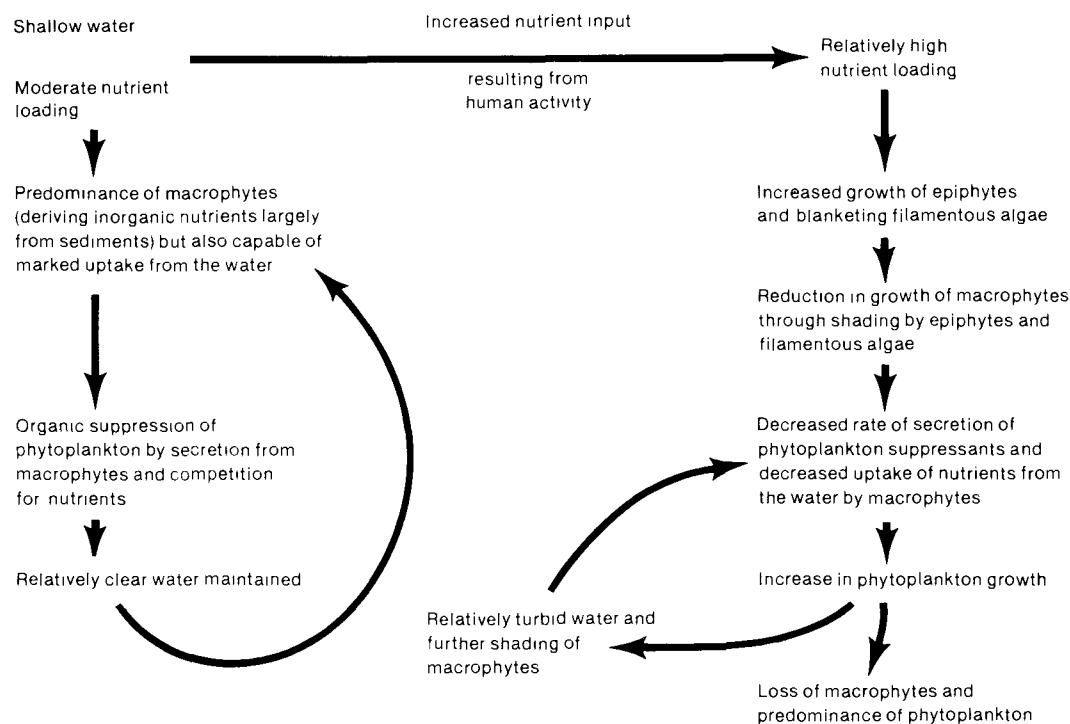


Figure 15. Diagram showing macrophyte decline in progressively nutrient-enriched freshwater (from Phillips and others, 1978).

In the tidal river, the site with the greatest light penetration contained naturally occurring vegetation, but light penetration at the vegetated sites in the transition zone was less than that at most of the nonvegetated intensive sites. Some historical Secchi disk data were found for the period 1968-69 (table 20; Jaworski, 1969), but the number of samples was not sufficient to perform a statistical analysis for significant differences. Summer transparencies appear to be lower, on the average, in 1968-69, when massive algal blooms occurred in the tidal river and transition zone (Jaworski, 1969).

There is an inverse relationship between both epiphyte chlorophyll *a* biomass and epiphyte dry weight and light transmittance in the tidal river. Epiphytes depress the photosynthesis of macrophytes (Sand-Jensen, 1977) by attenuating light and decreasing  $\text{HCO}_3^-$  (bicarbonate-ion) diffusion at the leaf surface.

Sand-Jensen reported that at light saturation and  $\text{HCO}_3^-$  concentrations between 0 milliequivalents/L and 2.55 milliequivalents/L, the rate of photosynthesis of leaves with epiphytes was lower than the rate of photosynthesis of the same leaf material without epiphytes. The inhibition of photosynthesis was greatest at low  $\text{HCO}_3^-$  concentration. Sand-Jensen stated that the reduced effects of the epiphytes at high  $\text{HCO}_3^-$  concentrations were due to increased diffusion of  $\text{HCO}_3^-$  into the macrophyte cells.

At a constant  $\text{HCO}_3^-$  concentration of (1.7 milliequivalent/L) with varying light intensity, Sand-Jensen found epiphytes reduced photosynthesis. At light intensities above 332  $\text{E}/\text{m}^2/\text{s}$ , photosynthesis was reduced about 31 percent. From 332  $\text{E}/\text{m}^2/\text{s}$  to 20  $\text{E}/\text{m}^2/\text{s}$ , photosynthesis decreased almost linearly to about 58 percent. Sand-Jensen suggested that the

shading effect is probably more important than relative  $\text{HCO}_3^-$  uptake if the leaf is not light saturated.

Epiphyte dry weight in the tidal river during 1981 was not significantly higher than in the transition zone. Epiphyte chlorophyll *a* varied significantly between sites in the tidal river. Washington Channel, Elodea Cove, and Rosier Bluff generally had significantly higher mean chlorophyll *a* biomass than the transition zone, but chlorophyll *a* biomass at Neabsco Bay and Goose Island--the sites with least transplant success--was not significantly different from that in the transition zone.

Water quality appears to have improved in the tidal river since the decades of the 1960's and 1970's, and excessive epiphyte growth and phytoplankton competition may be less important factors in the survival of submersed aquatic vegetation now than during that period. Figures 16 and 17 show the relationship between total dissolved nitrogen, total dissolved phosphorus, and total biomass in the tidal river and estuary during the spring, summer and fall of 1981. Phosphorus concentrations are very similar in the tidal river and in the transition zone, but decrease in the estuary. Nitrogen concentrations are highest in the tidal river downstream of the Blue Plains Sewage Treatment Plant. An update of Jaworski's (1971) graph (fig. 18) shows that the loads of phosphorus and organic carbon contributed by the sewage-treatment plants have reduced to 1950 loads after peaking in the 1960's and 1970's. The nitrogen load contributed by the sewage-treatment plant remains high. In terms of the overall yearly nutrient budget, the river contributes much more nitrogen and phosphorus where it enters the system at Little Falls than do the sewage treatment plants, except at periods of low flow when the contribution of the two sources is approximately equal.

If nutrients from increasing loads from the sewage treatment plant were a factor in eliminating submersed aquatic vegetation populations, it is logical to ask why submersed aquatic vegetation has not returned to the river above the influence of the plant. The beds at Washington Channel near National Airport are the only viable populations found above Blue Plains Sewage Treatment Plant. The sediments out in the main river above the plant are fine-grained and unstable. They may not offer sufficient anchoring for a submersed aquatic vegetation population, especially during large stream flows in the spring. Additionally, the sedimentation rate in this reach is quite high and the flats are frequently exposed to drying and freezing at low tides.

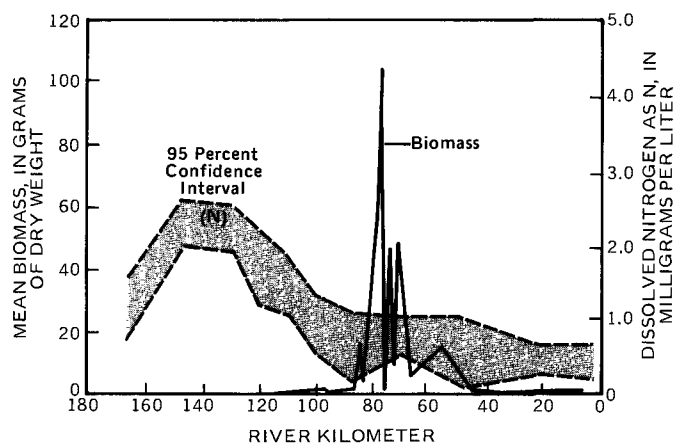
As to the question of why submersed aquatic vegetation has survived in the transition zone, existence of complex macrophyte-epiphyte-phytoplankton interactions in the tidal Potomac River and Estuary can

**Table 20.** Comparison of Secchi-disk water-transparency measurements in the tidal Potomac River from 1968-69 and 1978-82

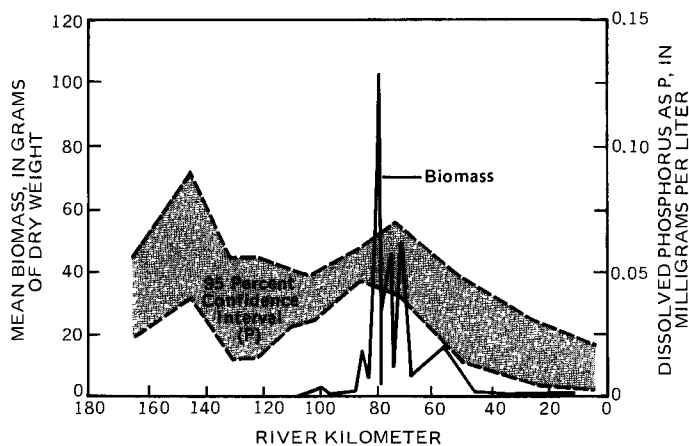
[Depth in meters]

Site	Spring						Summer					
	1968-69			1978-82			1968-69			1978-82		
	Mean	Range	Number of samples	Mean	Range	Number of samples	Mean	Range	Number of samples	Mean	Range	Number of samples
Washington Channel	.55	.58-.64	4	.77	.6-1.0	9	.37 <sup>1</sup>	.13-.61	7	1.13		1
Goose Island	.52	.41-.66	6	.46	.30-.63	9	.33	.14-.61	5	.63		1
Rosier Bluff	.57	.46-.71	4	.56	.40-.81	14	.37	.20-.53	10	.55	.45-.77	6
Elodea Cove	.57	.46-.66	4	.60	.38-.96	9	.36 <sup>1</sup>	.28-.51	8	.60	.40-.85	4
Neabsco Bay	.54	.51-.56	3	.42	.36-.56	6	.45	.26-.61	6	.48		1

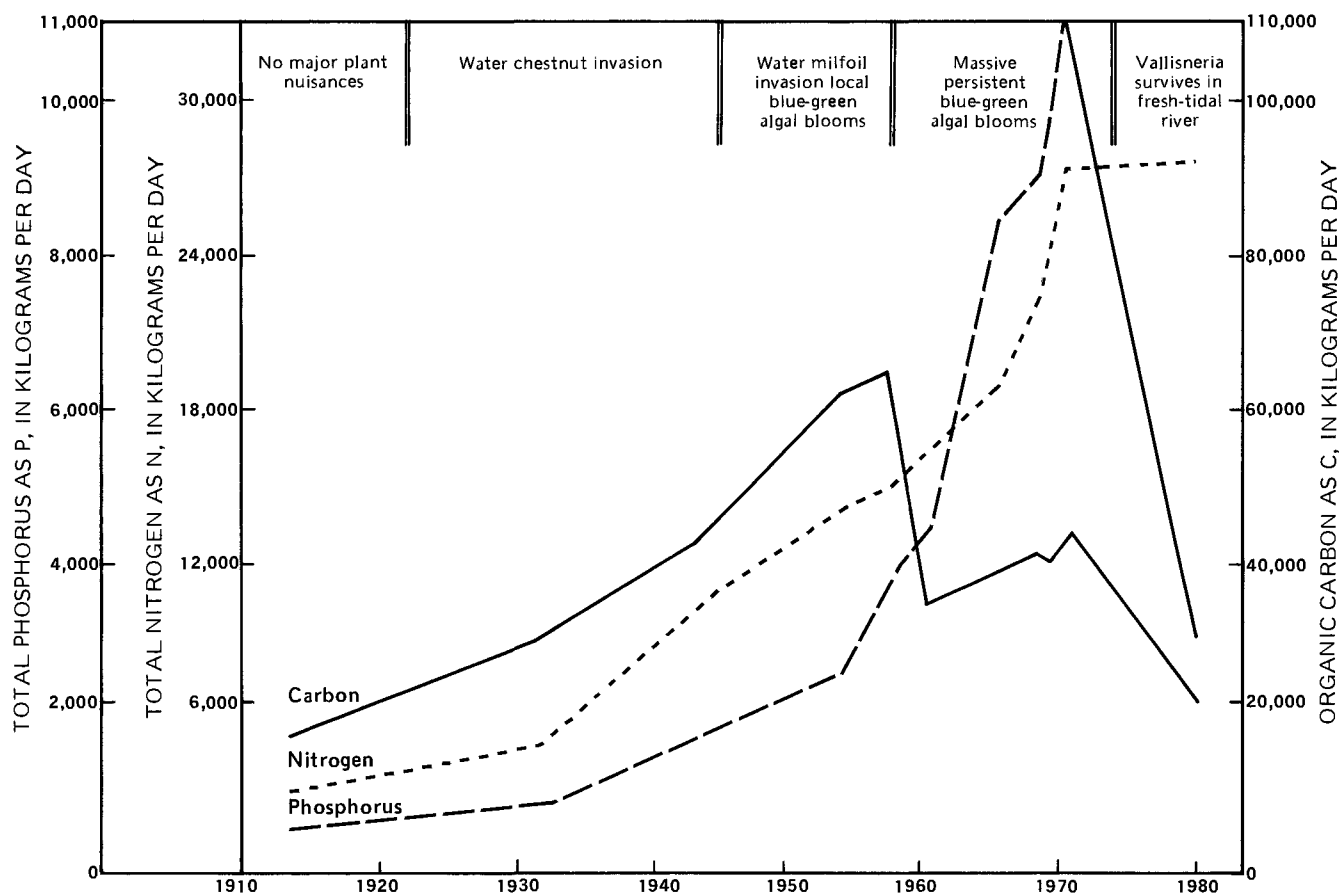
<sup>1</sup>Median values for each of these stations was 0.30 m. Other median values for stations were very close to mean values.



**Figure 16.** Variation of submersed aquatic vegetation biomass and dissolved nitrogen as a function of distance from the mouth of the Potomac Estuary, 1979-80.



**Figure 17.** Variation of submersed aquatic vegetation biomass and dissolved phosphorus with respect to distance from the mouth of the Potomac Estuary, 1979-80.



**Figure 18.** Wastewater nutrient enrichment trends and ecological effects, upper tidal Potomac River, (modified from Jaworski and others, 1971).



neither be corroborated nor rejected. The salinity variations and related osmotic changes, as well as flushing rate, may limit or exclude certain freshwater-adapted and true mesohaline plankton and epiphytes from the transition zone, thereby permitting macrophytes to survive. Figure 19 compares the chlorophyll *a* concentration and submersed aquatic vegetation biomass for spring, summer and fall of 1981. It is clear that there is a drop in chlorophyll *a* concentration in the transition zone that is related to higher salinity in this zone. The correlation of high submersed aquatic vegetation biomass with low chlorophyll *a* concentration is shown in the summer and the fall, but is not so clear in the spring when the salt front is generally near or below the Rt. 301 Bridge (fig. 3). Major shifts in the salinity gradients caused by floods or droughts would permit epiphytes and phytoplankton to enter the vegetated zone, but several years may be required to eliminate submersed aquatic vegetation populations, thereby producing noticeable, but temporary effects.

### Grazing

The failure of unprotected transplants to survive and the frequent cropping of plants at the transplant sites suggest that grazing (clipping off) of vegetation (perhaps by turtles, muskrats, waterfowl or fish) is a factor that limits plant success. Grazers may prevent establishment of submersed aquatic vegetation in the tidal river unless a certain critical bed size and thickness of rhizome mat are achieved.

### Substrate

During the 1978 survey, most of the plant populations appeared to be growing on sand-based sediments rather than on the softer silts and silt-clays. However, in 1979 and 1980, several additional populations of plants were located growing on finer substrates in sheltered areas. Nicholson and others (1975) found no clear correlation of macrophytes with sediment types except in the case of weakly-rooted plants (*Ceratophyllum*, *Elodea canadensis*) whose growth is favored by fine-grained sediments. They felt that other factors such as differing siltation tolerances or differences in water circulation, might be responsible for distribution of macrophytes. Where fetches are large, the plants may be easily washed out of the fine sediments. Possibly some growth-reducing substance is absorbed on the finer sediments or some unusual condition is associated with these sediments. Our sampling results suggest that trace metal concentrations in sediments are not a factor; vegetated and nonvegetated

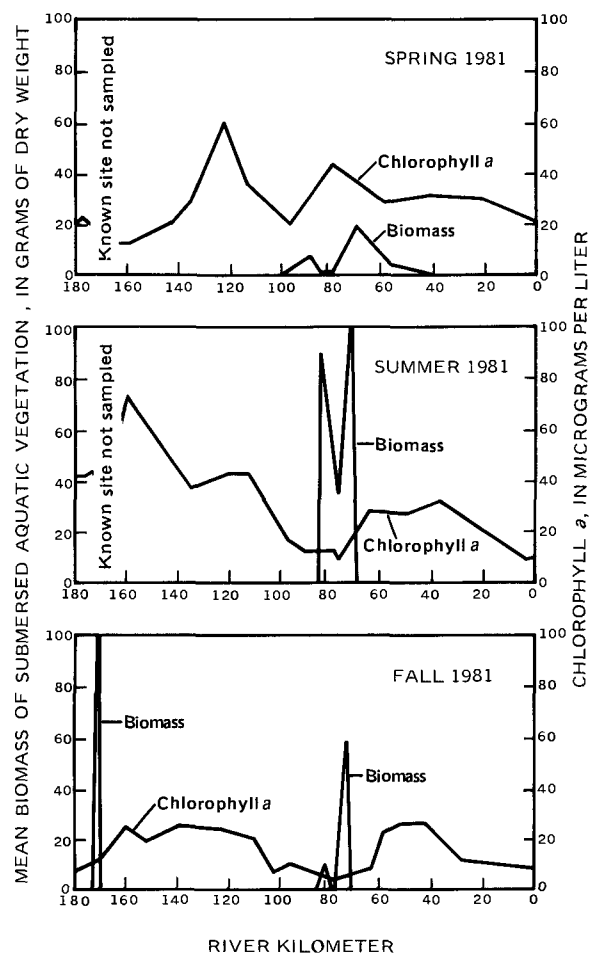


Figure 19. Variation of submersed aquatic vegetation biomass and chlorophyll *a* concentrations with respect to distance from the mouth of the Potomac Estuary, 1981.

sites on Nanjemoy Creek had very similar trace metal concentrations, and trace metal concentrations (Zn, Pb, and Mn) in tidal river sediments did not differ substantially from those in Nanjemoy Creek (tables 8 and 12).

## ENVIRONMENTAL IMPLICATIONS

The decline in submersed aquatic vegetation reflects a change in historical ecosystem conditions. In an unpolluted riverine or estuarine environment, macrophytes and phytoplankton both utilize a limited nutrient supply and provide a vital link in the food chain. Populations fluctuate in response to natural stresses, such as changes in salinity caused by drought or high stream flows. When subjected to gross or even subtle man-made environmental perturbations, the ecosystem may change. The decline or absence of

submersed aquatic vegetation in freshwater environments generally is accompanied by a decline in macroinvertebrate, fish, turtle, and waterfowl populations and (or) replacement of sensitive species by more pollution-tolerant species (Haslam, 1978; Moll, 1980).

The vanishing submersed aquatic vegetation in the Chesapeake Bay area represent a widespread problem rather than an isolated or unusual phenomenon (Mills and others, 1966; Jupp and Spence, 1977b; Morgan, 1970; Orth and others, 1982). Aquatic plant beds along the Illinois River were luxuriant in 1930; coontail, elodea, pondweeds, naiads, and wildcelery filled the river and flood-plain lakes. Following a series of severe population declines and temporary recoveries, the aquatic plants were largely eradicated between the mid-1950's and 1966 (Mills and others, 1966). During the same period, most of the bottom fauna, including mollusca such as the fingernail clam (*Sphaeriidae*) disappeared. Submerged macrophytes declined in Loch Leven Scotland, between 1950 and 1972 following eutrophication (Jupp and Spence, 1977a, 1977b).

Historically, the tidal waters of the Potomac River, which typify the diversity of aquatic habitats found throughout the Chesapeake Bay system, were the prime wintering areas for thousands of ducks, geese, and swans. The Chesapeake Bay was so important to waterfowl that large portions of the continental population of some species wintered there. Similarly, the Illinois River was a popular resting place for diving ducks on their fall and spring migrations (Mills and others, 1966), and Loch Leven, Scotland, was used during the summer by mute swans (*Cygnus olor*), coots (*Fulica atra*), and pochards (*Aythya ferina*) (Jupp and Spence, 1977b).

Loss of aquatic plants, and, in some cases, the concurrent loss of benthic invertebrates, has adversely affected the quality of wintering habitats for many waterfowl, particularly the inland diving ducks (tribe Aythyini, commonly called pochards or bay bucks). Continental populations of canvasbacks and redhead ducks, two prized game species, have declined sharply during this century. Although losses of prairie breeding habitat, vulnerability to hunting, and other factors are often implicated in this decline, it is clear that loss of quality wintering or migratory habitat is an important factor. When vegetation declines, waterfowl must modify their food habits or move to more favorable habitats. A more lengthy discussion of the implications of loss of submersed aquatic vegetation to waterfowl in the tidal Potomac River and Estuary, and in the Chesapeake Bay area in general, is found in Carter and Haramis (1980) and Boynton and Heck (1982).

Loss of aquatic plants has a variable effect upon wildlife species depending upon their adaptability. For example, although the waterfowl populations using the

Illinois River have been impacted by the loss of aquatic vegetation and bottom fauna, virtually all of the turtle populations are doing well. Moll (1980) explains that turtle survival amidst drastically changing environmental conditions is due to the longevity of turtles and their capacity for behavioral and physiological adaptation. Although turtles once used rooted aquatic plants for food and shelter, they have now switched from a herbivorous to omnivorous diet thriving on drowned insects, detritus and carrion. Pollution-resistant species, such as the Asiatic clam, *Corbicula fluminea*, which has recently invaded the Illinois River (Mills and others, 1966) and the Potomac River (Dresler and Cory, 1980), may serve as a new food source for turtles and waterfowl. Similarly, man-made debris and pollution-induced fish kills may provide substitute shelter and food for remaining wildlife species.

Loss of submersed aquatic vegetation from the tidal Potomac River has implications beyond its effects on wildlife. The habitat values of submersed aquatic vegetation are summarized by Boynton and Heck (1982). Substantial beds of submersed aquatic vegetation can modify littoral-zone sediment dynamics, trapping sediment and consolidating sediments at the surface (Orth, 1977; Boynton and Heck, 1982). Submersed aquatic vegetation reduces turbidity and increases water transparency. Its role in oxygenating the water in the reach near Washington, D.C. has been cited unequivocally (Secretary of the Treasury, 1933; Cumming and others, 1916). Submersed aquatic vegetation can also reduce nutrient concentrations, at least when loading rates are moderate. Thus, the loss of submersed aquatic vegetation from the tidal Potomac River implies the loss of an ecosystem component that provides food and shelter for invertebrates and vertebrates, aids in cycling nutrients and maintaining a good nutrient balance, oxygenates the water during the warm, low flow, summer months, and improves water clarity during the growing season. A detailed discussion of submersed aquatic vegetation functions and values can be found in Boynton and Heck (1982).

## SUMMARY AND CONCLUSIONS

From 1978 through 1982, the U. S. Geological Survey, with the assistance of the U. S. Fish and Wildlife Service, studied the distribution and abundance of submersed aquatic vegetation in the tidal Potomac River and Estuary. Sixteen species of submersed aquatic plants were identified, fourteen vascular plants and two species of the algae *Chara*. The majority of the plants are located in the transition zones of the Potomac River and Wicomico River

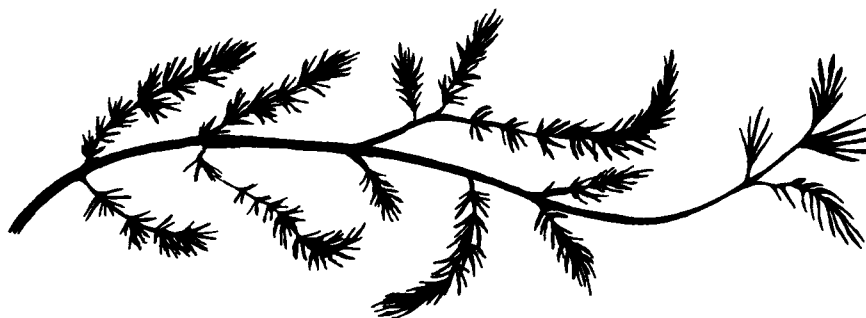
tributary, with a few isolated populations in the tidal river and estuary. Biomass was extremely variable from year to year and season to season. *Vallisneria americana*, *Zannichellia palustris*, *Ruppia maritima* and *Potamogeton perfoliatus* were the most abundant and widespread species.

The present distribution and abundance are very different from that in the early 1900's. Flats in the tidal river were covered with lush vegetation including *Vallisneria* and *Potamogeton* spp. The estuary had an abundance of *Zostera marina*, a species which was reported by Orth and others (1982) as abundant in 1965 as well.

It is difficult to isolate the factors responsible for the decline of submersed aquatic vegetation in the tidal Potomac River and Estuary. The most likely reasons for their almost complete disappearance from the tidal river include extensive storm damage in the late 1930's, increasing nutrient enrichment with a shift in the macrophyte-epiphyte-phytoplankton balance, a change in light availability, and grazing before adequate rhizome mats or minimum bed sizes were established. Salinity also influences the extent of species success in the

transition zone or estuary. Species tolerance to all of the above factors and other more minor factors may play a role in determining success or failure. Salinity dynamics in the transition zone may account for the presence of abundant vegetation of many species.

Loss of submersed aquatic vegetation is a symptom of ecosystem change, just as massive algal blooms or choking masses of tolerant vegetation are a symptom of nutrient overenrichment. Populations fluctuate in response to natural stresses such as drought and storm flows, but man-made environmental perturbations may exceed the limits of even the most tolerant species. Populations of animals dependent upon submersed aquatic vegetation for food or shelter either decline in response to the loss of submersed aquatic vegetation or turn to alternate sources. Generally, if ecosystem conditions improve, submersed aquatic vegetation should return. The expansion of the large natural bed of *Vallisneria* at Haines Point, and the partial success of the tidal-river transplants may indicate an improvement in water-quality conditions, just as has the return of bass fishing to the Washington, DC, metropolitan area (Almy, 1982).



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