United States
Environmental Protection
Agency

Office of Water
Regulations and Standards
Washington, DC 20460

Water

EPA

Technical Support Manual: Waterbody Surveys and Assessments for Conducting Use Attainability Analyses

Volume II: Estuarine Systems

FOREWORD

The Technical Support Manual: Water Body Surveys and Assessments for Conducting Use Attainability Analyses in Estuarine Systems contains guidance prepared by EPA to assist States in implementing the revised Water Quality Standards Regulation (48 FR 51400, November 8, 1983). This document addresses the unique characteristics of estuarine systems and supplements the Technical Support Manual: Water Body Surveys and Assessments for Conducting Use Attainability Analyses (EPA, November, 1983). The central purpose of these documents is to provide guidance to assist States in answering three central questions:

(1) What are the aquatic protection uses currently being achieved in the water body?

(2) What are the potential uses that can be attained based on the physical, chemical and biological characteristics of the waterbody? and

(3) What are the causes of any impairment of the uses?

Consideration of the suitability of a water body for attaining a given use is an integral part of the water quality standards review and revision process. EPA will continue to provide guidance and technical assistance to the States in order to improve the scientific and technical bases of water quality standards decisions. States are encouraged to consult with EPA at the beginning of any standards revision project to agree on appropriate methods before the analyses are initiated, and to consult frequently as they are conducted.

Any questions on this guidance may be directed to the water quality standards coordinators located in each of the EPA Regional Offices or to:

Elliot Lomnitz
Criteria and Standards Division (WH-585)
401 M Street S.W.
Washington, D.C. 20460

Steven Schatzow, Director
Office of Water Regulations and Standards

TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

EPA's Office of Water Regulations and Standards has prepared guidance to accompany changes to the Water Quality Standards Regulation (48 FR 51400). Programmatic guidance has been compiled and published in the Water Quality Standards Handbook (EPA, December 1983). This document discusses the water quality review and revision process; general programmatic guidance on mixing zones, flow, and economic considerations; use attainability analyses; and site specific criteria.

One of the major pieces of guidance in the Handbook is "Water Body Surveys and Assessments for Conducting Use Attainability Analyses." This guidance lays out the general framework for designing and conducting a use attainability analysis, whose objective is to answer the questions:

1. What are the aquatic life uses currently being achieved in the water body?

2. What are the potential uses that can be attained, based on the physical, chemical and biological characteristics of the water body?

3. What are the causes of impairment of the uses?

Technical guidance on conducting water body surveys and assessments was provided in the Technical Support Manual: Water Body Surveys and Assessments for Conducting Use Attainability Analyses (EPA, November 1983) in response to requests by several States for additional information. The Technical Support Manual essentially provides methods and tools for freshwater evaluations, but does not cover estuarine water bodies. The chapters presented in this volume address those considerations which are unique to the estuary. Those factors which are common to the freshwater and the estuarine system -- chemical evaluations in particular, are not discussed in this volume. Thus it is important that those who will be involved in the water body survey should also consult the 1983 Technical Support Manual. The methods and procedures offered in these guidance documents are optional and the States may apply them selectively, or they may use their own techniques or methods for conducting use attainability analyses.

The technical material presented in this volume deals with the major physical, chemical and biological attributes of the estuary: tides and currents, stratification, substrate characteristics; the importance of salinity, dissolved oxygen and nutrient enrichment; species diversity, plant and animal populations, and physiological adaptations which permit freshwater or marine organisms to survive in the estuary.

Given that estuaries are very complex receiving waters which are highly variable in description and are not absolutes in definition, size, shape, aquatic life or other attributes, those who will be performing use attainability analyses on estuarine systems should consider this volume as a frame of reference from which to initiate study design and execution, but not as an absolute guide.

CHAPTER II

PHYSICAL AND CHEMICAL CHARACTERISTICS

INTRODUCTION

The term estuary is generally used to denote the lower reaches of a river where tide and river flows interact. The generally accepted definition for an estuary was provided by Pritchard in 1952: "An estuary is a semi-enclosed coastal body of water having a free connection with the open sea and containing a measureable quantity of seawater." This description has remained remarkably consistent with time and has undergone only minor revisions (Emery and Stevenson, 1957; Cameron and Pritchard, 1963). To this day, such qualitative definitions are the most typical basis for determining what does and what does not constitute an estuary.

Estuaries are perhaps the most important social, economic, and ecologic regions in the United States. For example, according to the Department of Commerce (DeFalco, 1967), 43 of the 110 Standard Metropolitan Statistical Areas are on estuaries. Furthermore, recent studies indicate that many estuaries, including Delaware Bay and Chesapeake Bay, are on the decline. Thus, the need has arisen to better understand their ecological functions to define what constitutes a "healthy" system, to define actual and potential uses, to determine whether designated uses are impaired, and to determine how these uses can be preserved or maintained. This is the basis for the Use Attainability Analysis.

As part of such a program, there is a need to define impact assessment procedures that are simple, in light of the wide variability among estuaries, yet adequately represent the major features of each system studied. Estuaries are three-dimensional waterbodies which exhibit variations in physical and chemical processes in all three directions (longitudinal, vertical, and lateral) and also over time. However, following a careful consideration of the major physical and chemical processes and the time scales involved in use assessment, one can often define a simplified version of the prototype system for study.

In this chapter, a discussion is presented of important estuarine features and of major physical processes. A description of chemical evaluations is also presented, although the discussion herein is very limited since an extensive presentation was included in the earlier U.S. EPA Technical Support Manual (U.S. EPA November 1983). From this background, guidance for use attainability evaluations is given which considers the various assumptions that may be made to simplify the complexity of the analysis, while retaining an adequate description of the system. Finally, a framework for selecting appropriate desk-top and computer models for use attainability evaluations is outlined.

PHYSICAL PROCESSES

Introduction

Estuarine flows are the result of a complex interaction of:

- o tides,
- o wind shear,
- o freshwater inflow (momentum and buoyancy),
- o topographic frictional resistance,
- o Coriolis effect,
- o vertical mixing, and
- o horizontal mixing.

In performing a use attainability study, one must simplify the complex prototype system by determining which of these effects or combination of effects is most important at the time scale of the evaluation. To do this, it is necessary to understand each of these processes and their impacts on the evaluation. A complete description of all of the above is beyond the scope of this report. Rather, illustrated are some of the features of each process, particularly in terms of magnitude and time scale.

Tides

Tides are highly variable throughout the United States, both in amplitude and phase. Figure II-1 (NOAA 1983) shows some typical tide curves along the Atlantic, Gulf of Mexico, and Pacific Coasts. Tidal amplitude can vary from 1 foot or less along the Gulf of Mexico (e.g., Pensacola, Florida) to over 30 feet in parts of Alaska (e.g., Anchorage) and the Maritime Provinces of Canada (e.g., the Bay of Fundy). Tidal phasing is a combination of many factors with differing periods. However, in the United States, most tides are predominantly based on 12.5-hour (semidiurnal), 25-hour (diurnal) and 4-day (semi-lunar) combinations. In some areas, such as Boston (Figure II-1), the tide is predominantly semidiurnal with 2 high tides and 2 low tides each day. In others, such as along the Gulf of Mexico, the tides are more typically mixed.

Tidal power is directly related to amplitude. This potential energy source can promote increased mixing through increased velocities and interactions with topographic features.

Wind

In many exposed bays or estuaries, particularly those in which tidal forcing is smaller, wind shear can have a tremendous impact on circulation patterns at time scales of a few hours to several days. An example is Tampa Bay on the West Coast of Florida, where tidal ranges are approximately 3 feet, and the terrain is generally quite flat. Wind can be produced from localized thunderstorms of a few hours duration, or from frontal movements with durations on the order of days. Unlike tides, wind is unpredictable in a real time sense. The usual approach to studying wind driven circulations is to develop a wind rose (Figure II-2) from local meteorological data, and base the study of impacts on statistically significant magnitudes and directions, or on winds that might produce the most severe impact.

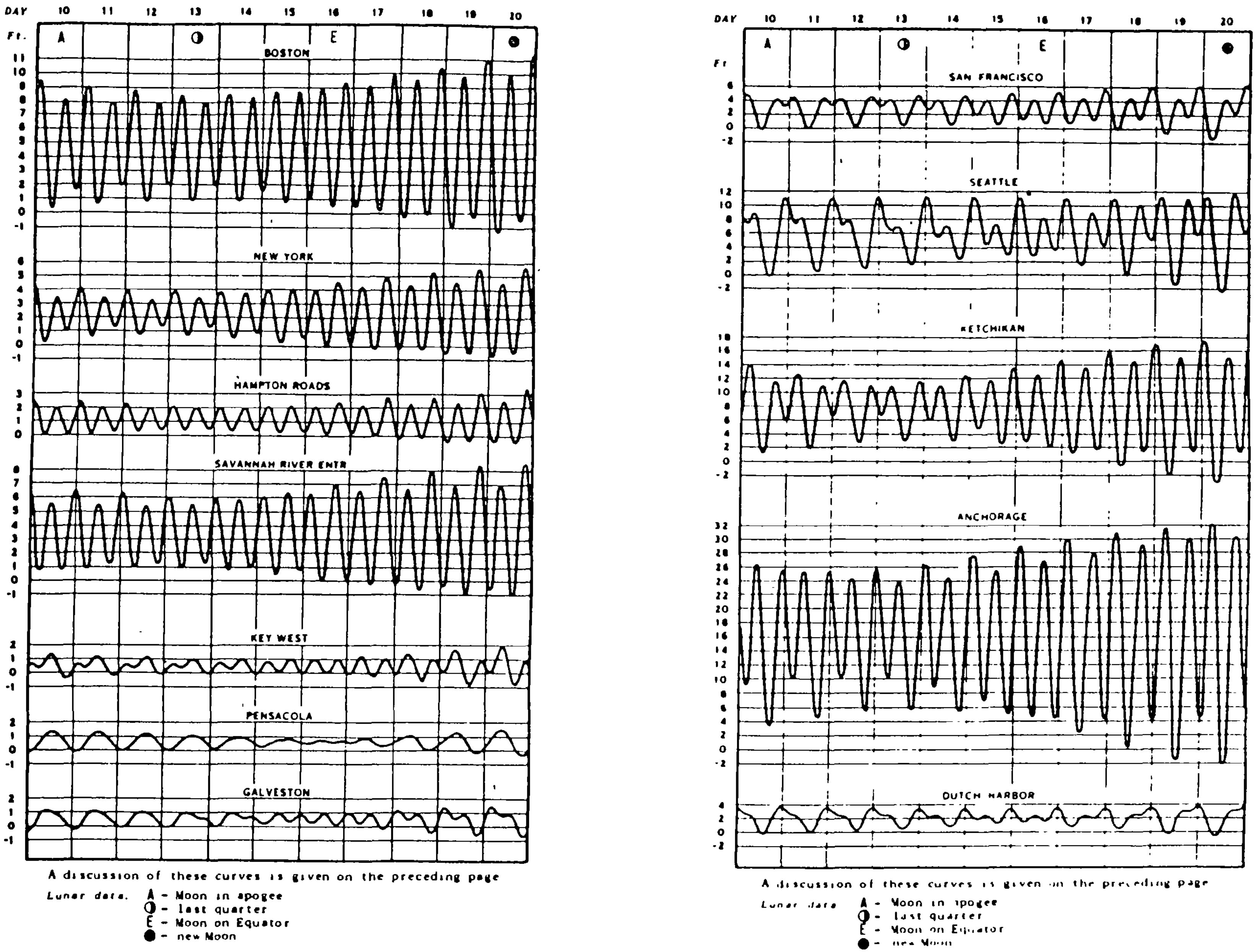


Figure II-1. Typical Tide Curves for United States Ports.

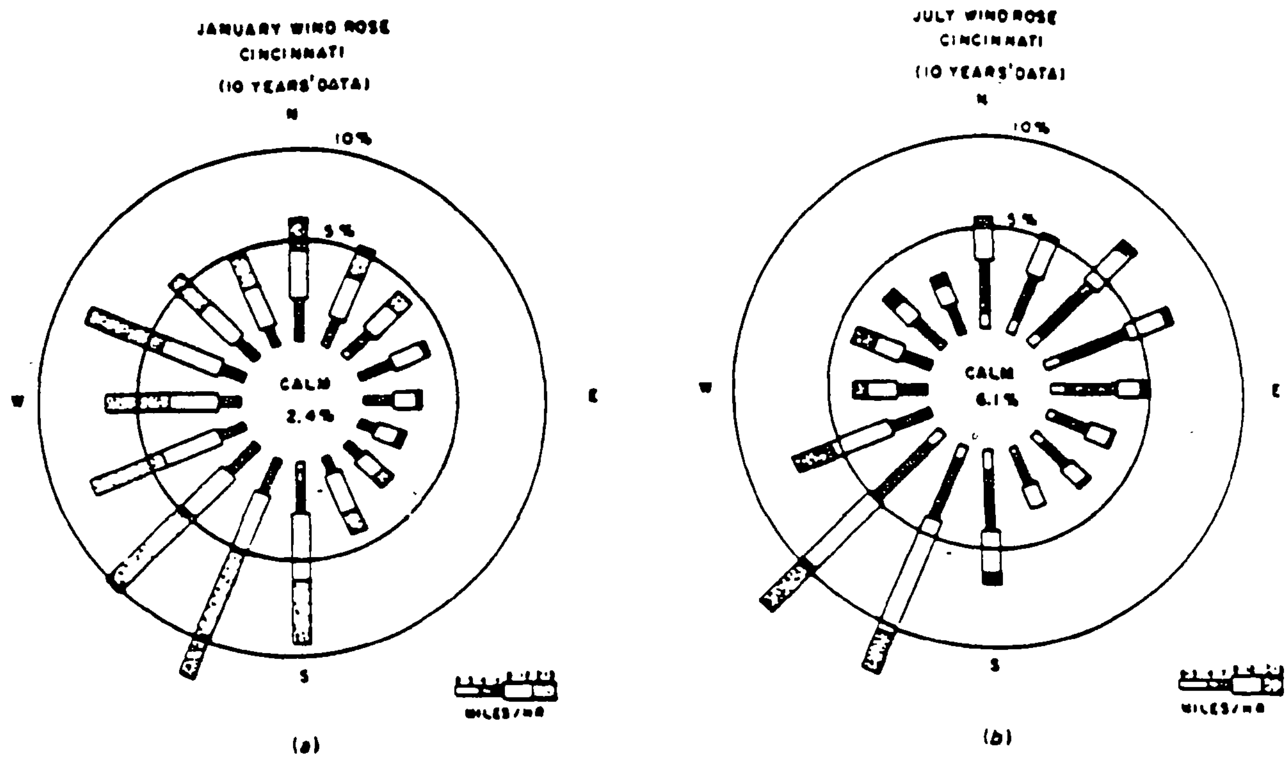


Figure II-2. Typical Wind Rose. (H.C. Perkins, 1974)

Freshwater Inflows

Freshwater inflows from a major riverine source can be highly variable from day to day and season to season. At the shorter time scale, the river may be responding to a localized thunderstorm, or the passage of a front. In many areas, however, the frequency of these events tends to group into a season (denoted the wet season) which is distinct from the remainder of the year (the dry season). The average monthly streamflow distributions in Figure II-3 illustrate that in Virginia the wet season is typically from December to May and comes mainly from portal systems. In Florida, however, the trend is reversed, with the wet season coinciding with the summer months when localized thunderstorms predominate.

It is important to consider the effect of freshwater flows on estuarine circulation, because streamflow is the only major mechanism which produces a net cross sectional flow over long averaging times. A common approach is to represent the estuary as a system drive by net freshwater flows in the downstream directory with other effects averaged out and lumped into a dispersion-type parameter. When using this assumption to evaluate the estuary system, one must weigh the consequences very carefully.

Freshwater is less dense and tends to "float" over seawater. In some cases, freshwater may produce a residual 2-layer flow pattern (such as in the James Estuary (Virginia) or Potomac Rivers) or even a 3-layer flow pattern (as in Baltimore Harbor). The danger is to treat such a distinctly 2-layer system as a cross-sectionally averaged, river driven system, and then try to explain why pollutants are observed upstream of a discharge point when no mechanism exists to produce this effect using a one-dimensional approach.

Friction

The estuary's topographic boundaries (bed and sides) produce frictional resistance to local currents. In some estuaries with highly variable geometries, this can produce a number of net nontidal (or tidally-averaged) effects such as residual eddies near headlands or tidal rectification. Pollutants trapped in residual eddies, perhaps from a wastewater treatment plant outfall, may have very large residence times that are not predictable from cross-sectionally averaged flows before such pollutants are flushed from the system.

Coriolis Effect

In wide estuaries, the Coriolis effect can cause freshwater to adhere to the right-hand bank (facing the open sea) so that the surface slopes upward to the right of the flow. The interface has an opposite slope to maintain geostrophic balance. For specific configurations and corresponding flow regimes, the boundary between outflow and inflow may actually cut the surface (Figure II-4a). This is the case in the lower reaches of the St. Lawrence estuary, for example, where the well-defined Gaspe current holds against the southern shore and counter flow is observed along the northern side. This effect is augmented by tidal circulation which forces ocean waters entering the estuary with the flood tide to adhere to the left side of the estuary (facing the open sea), and the ebb flow to the right side. Thus, as is often apparent from the surface salinity pattern in an estuary, the outflow is stronger on the right-hand side (Figure II-4b). The exact location and configuration of the saltwater/freshwater interface depends on the relative magnitude of the forces at play. Quantitative estimates of various mixing modes in estuaries are discussed below.

Vertical Mixing

All mixing processes are caused by local differences in velocities and by the fact that liquids are viscous (i.e., possess internal friction). In the vertical direction, the most common mixing occurs between riverine fresh waters and the underlying saline ocean waters.

If there were no friction, freshwater would flow seaward as a shallow layer on top of the seawater. The layer would become shallower and the velocity would decrease as the estuary widened toward its mouth. Friction between the two types of water requires a balancing pressure gradient down-estuary, explaining the salt wedge formation which deepens toward the mouth of the estuary, as seen in Figure II-5. Friction also causes mixing along the interface. A particularly well-defined salt wedge is observed in the estuary of the Mississippi River.

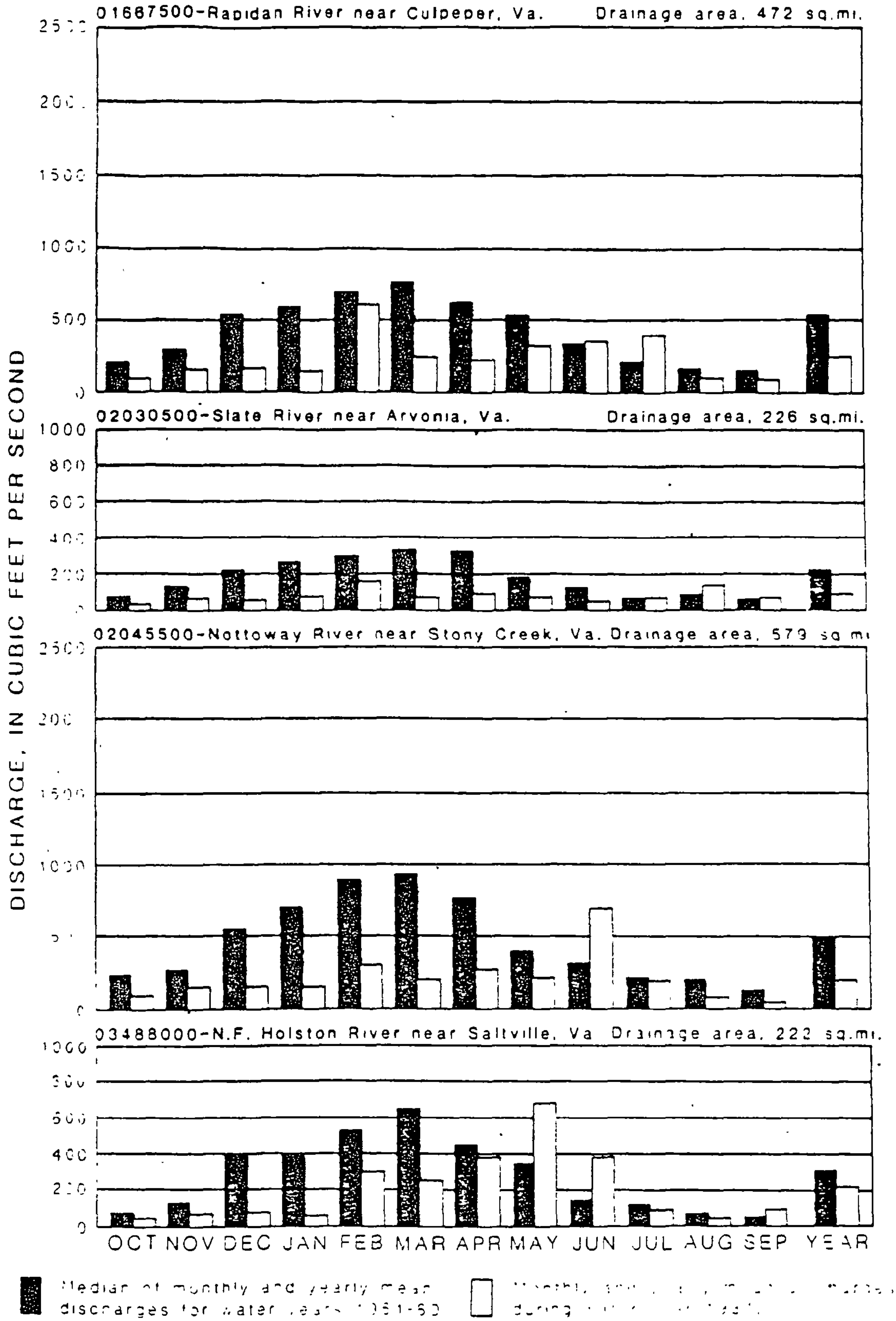
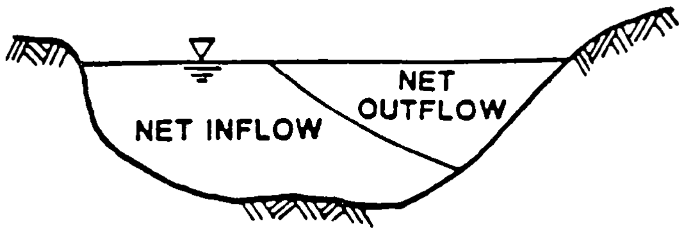
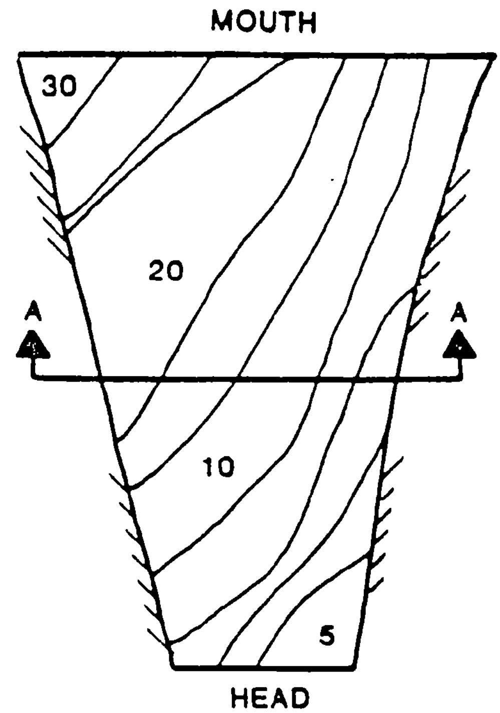


Figure II-3. Monthly Average Streamflows for location in Virginia. (from U. S. Geological Survey 1982)



a. Cross-section A-A looking Down-estuary.



b. Surface Salinity Distribution (ppt).

Figure II-4. Net Inflow and Outflow in a Tidal Estuary, Northern Hemisphere.

If significant mixing does not occur along the freshwater/saltwater interface, the layers of differing density tend to remain distinct and the system is said to be highly stratified in the vertical direction. If the vertical mixing is relatively high, the mixing process can almost completely break down the density difference, and the system is called well-mixed or homogeneous.

In sections of the estuary where there is a significant difference between surface and bottom salinity levels over some specified depth (e.g., differences of about 5 ppt or greater over about a 10 foot depth), the water column is regarded as highly stratified. An important impact of vertical stratification on use attainability is that the vertical density differences significantly reduce the exchange of dissolved oxygen and other constituents between surface and bottom waters. Consequently, persistent stratification can result in a depression of dissolved oxygen (DO) in the high salinity bottom waters that are cut off from the low salinity surface waters. This is because bottom waters depend upon vertical mixing with surface waters, which can take advantage of reaeration at the air-water interface, to replenish DO that is consumed as a result of organic materials within the water column and bottom sediments. In sections of the estuary exhibiting significant vertical stratification, vertical mixing of DO contributed by reaeration is limited to the low salinity surface waters.

As a result, persistent stratified conditions can cause the DO concentration in bottom water to fall to levels that cause stress on or mortality to the resident communities of benthic organisms.

Another potential impact of vertical stratification is that anaerobic conditions in bottom waters can result in increased release of nutrients such as phosphorus and ammonia-nitrogen from bottom sediments. During later periods or in sections of the estuary exhibiting reduced levels of stratification, these increased bottom sediment contributions of nutrients can eventually be transported to the surface water layer. These increased

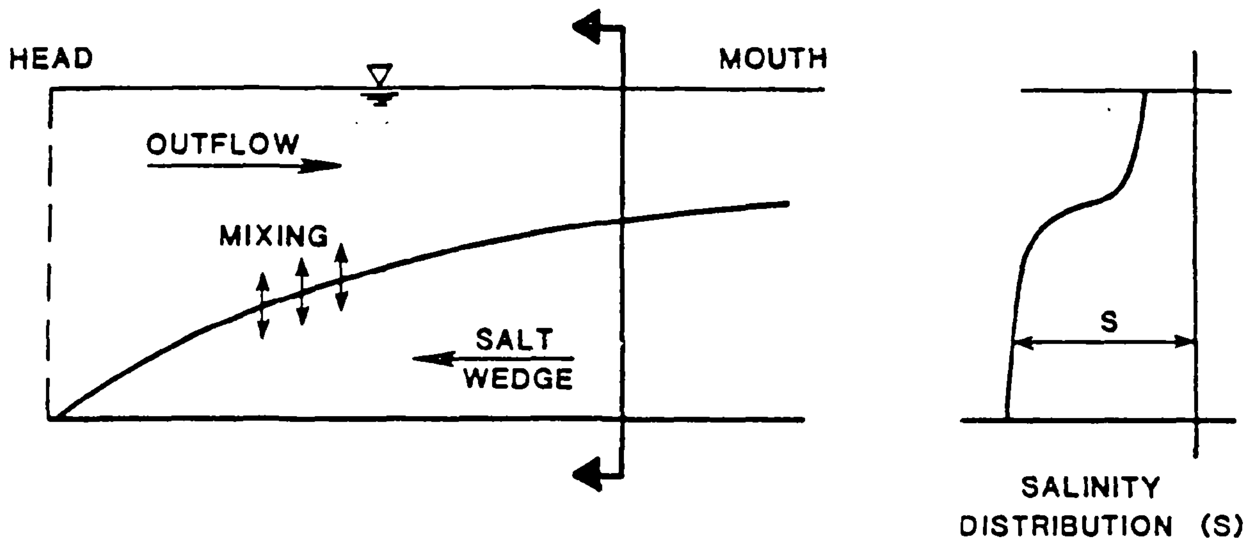


Figure II-5. Layered Flow in a Salt-wedge Estuary (Longitudinal Profile).

nutrient loadings on surface waters can result in higher phytoplankton concentrations that can exert diurnal DO stresses and reduced light penetration for rooted aquatic plants. In summary, the persistence and areal extent of vertical stratification is an important determinant of use attainability within an estuary.

Horizontal Mixing

Mixing also occurs in the horizontal plane, although it is often neglected in favor of vertical processes. As with vertical mixing, horizontal mixing is caused by localized velocity variations and internal friction, or viscosity. The velocity variations are usually produced by the interactions of topographic and bed or side frictional effects, resulting in eddies of varying sizes. Thus, horizontal constituent distributions tend to be broken down by differential advection, which when viewed as an average advection (laterally, or cross-sectionally) is called dispersion.

ESTUARINE CLASSIFICATION

Introduction

It is often useful to consider some broad classifications of estuaries, particularly in terms of features and processes which enable us to analyze them in terms of simplified approaches. The most commonly used groupings are based on geomorphology, stratification, circulation patterns, and time scales.

Geomorphological Classification

Over the years, a systematic structure of geomorphological classification has evolved. Dyer (1973) and Fischer et al. (1979) identify four groups:

- o Drowned river valleys (coastal plain estuaries),
- o Fjords
- o Bar-built estuaries, and
- o Other estuaries that do not fit the first three classifications.

Typical examples of North American estuaries are presented in Table II-1.

Coastal plain estuaries are generally shallow with gently sloping bottoms, with depths increasing uniformly towards the mouth. Such estuaries have usually been cut by erosion and are drowned river valleys, often displaying a dendritic pattern fed by several streams. A well-known example is Chesapeake Bay. Coastal plain estuaries are usually moderately stratified (particularly in the old river valley section) and can be highly influenced by wind over short time scales.

Bar built estuaries are bodies of water enclosed by the deposition of a sand bar off the coast through which a channel provides exchange with the open sea, usually servicing rivers with relatively small discharges. These

TABLE II-1. TOPOGRAPHIC ESTUARINE CLASSIFICATION

Type	Dominant Long-Term Process	Degree of Stratification	Examples
Coastal Plain	River Flow	Moderate	Chesapeake Bay, MD/VA James River, VA Potomac River, MD/VA Delaware Estuary, DE/NJ New York Bight, NY
Bar Built	Wind	Low or None	Little Sarasota Bay, FL Apalachicola Bay, FL Galveston Bay, TX Roanoke River, VA Albemarle Sound, NC Pamlico Sound, NC
Fjords	Tide	High	Alberni Inlet, B.C. Silver Bay, AL
Other Estuaries	Various	Various	San Francisco Bay, CA Columbia River, WA/OR

are usually unstable estuaries, subject to gradual seasonal and catastrophic variations in configuration. Many estuaries in the Gulf Coast and Lower Atlantic Regions fall into this category. They are generally a few meters deep, vertically well mixed and highly influenced by wind.

Fjords are characterized by relatively deep water and steep sides, and are generally long and narrow. They are usually formed by glaciation, and are more typical in Scandinavia and Alaska than the contiguous United States. There are examples along the Northwest Pacific Ocean, such as Alberni Inlet in British Columbia. The freshwater streams that feed a fjord generally pass through rocky terrain. Little sediment is carried to the estuary by the streams, and thus the bottom is likely to be a clean rocky surface. The deep water of a fjord is distinctly cooler and more saline than the surface layer, and the fjord tends to be highly stratified.

The remaining estuaries not covered by the above classification are usually produced by tectonic activity, faulting, landslides, or volcanic eruptions. An example is San Francisco Bay which was formed by movement of the San Andreas Fault System (Dyer, 1973).

Stratification

A second classification of estuaries is by the degree of observed stratification, and was developed originally by Pritchard (1955) and Cameron and Pritchard (1963). They considered three groupings (Figure II-6):

- The highly stratified (salt wedge) type
- Partially mixed estuary
- Vertically homogeneous estuary

Such a classification is intended for the general case of the estuary influenced by tides and freshwater inflows. Shorter term events, such as strong winds, tend to break down highly stratified systems by inducing greater vertical mixing. Examples of different types of stratification are presented in Table II-2.

In the stratified estuary (Figure II-6a), large freshwater inflows ride over saltier ocean waters, with little mixing between layers. Averaged over a tidal cycle, the system usually exhibits net seaward movement in the freshwater layer, and net landward movement in the salt layer, as salt water is entrained into the upper layer. The Mississippi River Delta is an example of this type of estuary.

As the interfacial forces become great enough to partially break down the density differences, the system becomes partially stratified, or partially well-mixed (Figure II-6b). Tidal flows are now usually much greater than river flows, and flow reversals in the lower layer may still be observed, although they are generally not as large as for the highly stratified system. Chesapeake Bay and the James River estuary are examples of this type.

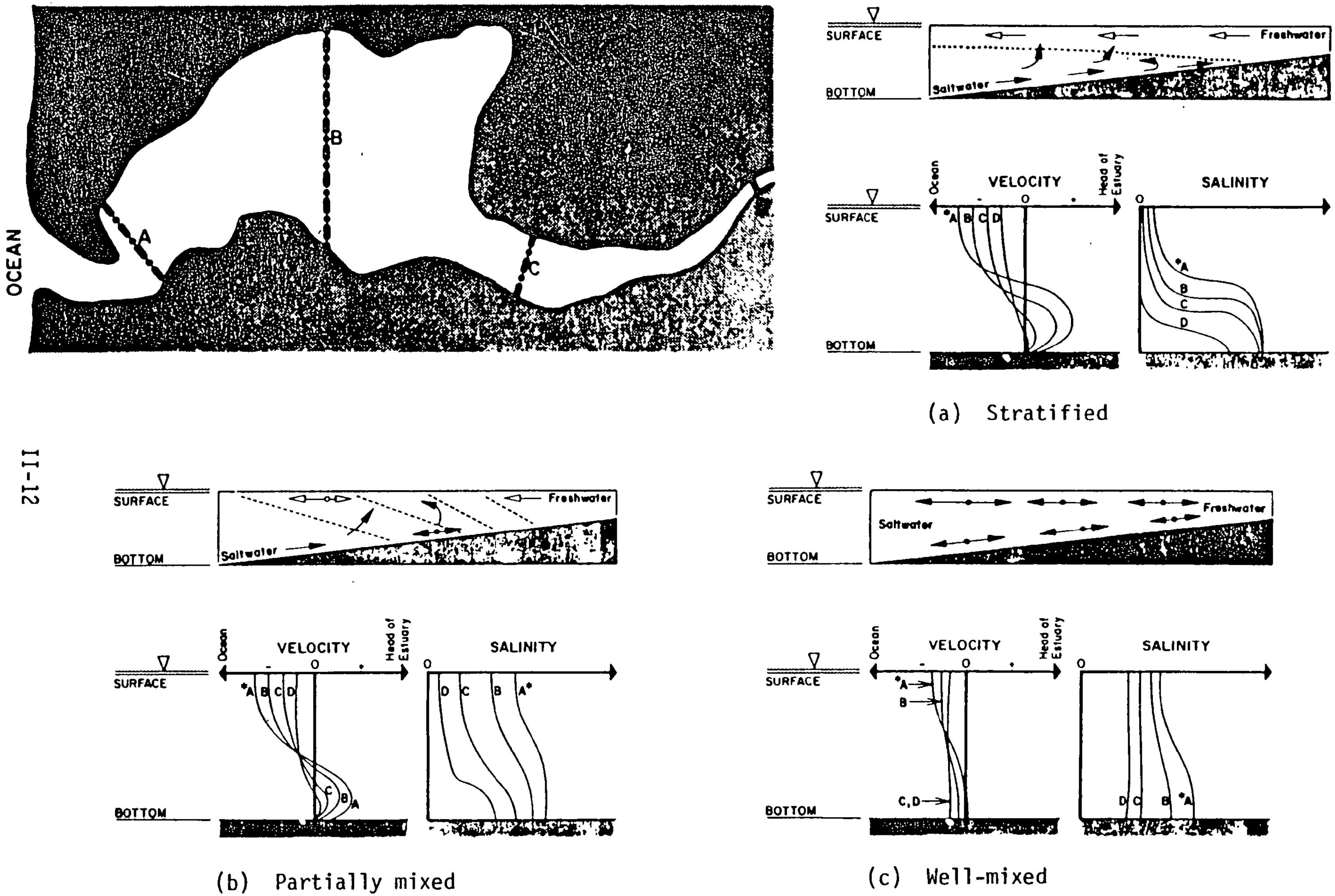


Figure II-6. Classification of Estuarine Stratification.

TABLE II-2. STRATIFICATION CLASSIFICATION

Type	River Discharge	Examples
Highly Stratified	Large	Mississippi River, LA Mobile River, AL
Partially Mixed	Medium	Chesapeake Bay, MD/VA James Estuary, VA Potomac River, MD/VA
Vertically Homogeneous	Small	Delaware Bay, DE/NJ Raritan River, NJ Biscayne Bay, FL Tampa Bay,FL San Francisco Bay, CA San Diego Bay, CA

In a well mixed system (Figure II-6c), the river inflow is usually very small, and the tidal flow is sufficient to completely break down the stratification and thoroughly mix the system vertically. Such systems are generally shallow so that the tidal amplitude to depth ratio is large and mixing can easily penetrate throughout the water column. The Delaware and Raritan River estuaries are examples of well-mixed systems.

Circulation Patterns

Circulation in an estuary (i.e., the velocity patterns as they change over time) is primarily affected by the freshwater outflow, the tidal inflow, and the effect of wind. In turn, the difference in density between outflow and inflow sets up secondary currents that ultimately affect the salinity distribution across the estuary. The salinity distribution is important in that it affects the distribution of fauna and flora within the estuary. It is also important because it is indicative of the mixing properties of the estuary as they may affect the dispersion of pollutants, flushing properties, and additional factors such as friction forces and the size and geometry of the estuary contribute to the circulation patterns.

The complex geometry of estuaries, in combination with the presence of wind, the effect of the earth's rotation (Coriolis effect), and other effects, often results in residual currents (i.e., of longer period than the tidal cycle) that strongly influence the mixing processes in estuaries. For example, uniform wind over the surface of an estuary produces a net wind drag force which may cause the center of mass of the water in the estuary to be displaced toward the deeper side since there is more water there. Hence a torque is induced causing the water mass to rotate.

In the absence of wind, the pure interaction of tides and estuary geometry may also cause residual currents. For example, flood flows through narrow inlets set up so-called tidal jets, which are long and narrow as compared to the ebb flows which draw from a larger area of the estuary, thus forcing a residual circulation from the central part of the estuary to the sides (Stommel and Farmer, 1952). The energy available in the tide is in part extracted to drive regular circulation patterns whose net result is similar to what would happen if pumps and pipes were installed to move water about in circuits. This is why this type of circulation is referred to as "tidal pumping" to differentiate from wind and other circulation (Fisher, et al., 1979).

Tidal "trapping" is a mechanism -- present in long estuaries with side embayments and small branching channels -- that strongly enhances longitudinal dispersion. It is explained as follows. The propagation of the tide in an estuary -- which represents a balance between the water mass inertia, the hydraulic pressure force due to the slope of the water surface, and the retarding bottom friction force -- results in main channel tidal elevations and velocities that are not in phase. For example, high water occurs before high slack tide and low water before low slack tide because the momentum of flow in the main channel causes the current to continue to flow against an opposing pressure gradient. In contrast, side channels which have less momentum can reverse the current direction faster, thus "trapping" portions of the main channel water which are then available for further longitudinal dispersion during the next flood tide.

Time Scales

The consideration of the time scales of the physical processes being evaluated is very important for any water quality study. Short-term conditions are much more influenced by a variety of short-term events which perhaps have to be analyzed to evaluate a "worst case" scenario. Longer term (seasonal) conditions are influenced predominantly by events which are averaged over the duration of that time scale.

The key to any study is to identify the time scale of the impact being evaluated and then analyze the forcing functions over the same time scale. As an example, circulation and mass transport in the upper part of Chesapeake Bay can be wind driven over a period of days, but is river driven over a period of one month or more. Table II-3 lists the major types of forcing functions on most estuarine systems and gives some idea of their time scales.

INFLUENCE OF PHYSICAL CHARACTERISTICS ON USE ATTAINABILITY

"Segmentation" of an estuary can provide a useful framework for evaluating the influence of estuarine physical characteristics such as circulation, mixing, salinity, and geomorphology on use attainability. Segmentation is the compartmentalizing of an estuary into subunits with homogeneous physical characteristics. In the absence of water pollution, physical characteristics of different regions of the estuary tend to govern the suitability for major water uses. Therefore, one major objective of segmentation is to subdivide the estuary into segments with relatively homogeneous physical characteristics so that differences in the biological communities among similar segments may be related to man-made alterations. Once the segment network is established, each segment can be subjected to a use attainability analysis. In addition, the segmentation process offers a useful management structure for monitoring conformance with water quality goals in future years.

The segmentation process is an evaluation tool which recognizes that an estuary is an interrelated ecosystem composed of chemically, physically, and biologically diverse areas. It assumes that an ecosystem as diverse as an estuary cannot be effectively managed as only one unit, since different uses and associated water quality goals will be appropriate and feasible for different regions of the estuary. The segmentation approach to use attainability assessment and water quality management has been successfully applied to several major receiving water systems, most notably Chesapeake Bay, the Great Lakes, and San Francisco Bay.

A potential source of concern about the construction and utility of the segmentation scheme for use attainability evaluations is that the estuary is a fluid system with only a few obvious boundaries, such as the sea surface and the sediment-water interface. Boundaries fixed in space are to be imposed on an estuarine system where all components are in communication with each other following a pattern that is highly variable in time. Fixed boundaries may seem unnatural to scientists, managers, and users, who are

TABLE II-3. TIME SCALES OF MAJOR PROCESSES

Forcing Function	Time Scale
TIDE	
One cycle	0.5-1 day
Neap/Spring	14 days
WIND	
Thunderstorm	1-4 hours
Frontal Passage	1-3 days
RIVER FLOW	
Thunderstorm	0.5-1 day
Frontal Passage	3-7 days
Wet/Dry Seasons	4-6 months

more likely to view the estuary as a continuum than as a system composed of separable parts. The best approach to dealing with such concerns is a segmentation scheme that stresses the dynamic nature of the estuary. The scheme should emphasize that the segment boundaries are operationally defined constructs to assist in understanding a changeable, intercommunicating system of channels, embayments, and tributaries.

In order to account for the dynamic nature of the estuary, it is recommended that estuarine circulation patterns be a prominent factor in delineating the segment network. Circulation patterns control the transport of and residence times for heat, salinity, phytoplankton, nutrients, sediment, and other pollutants throughout the estuary. Salinity should be another important factor in delineating the segment network. The variations in salinity concentrations from head of tide to the mouth typically produce a separation of biological communities based on salinity tolerances or preferences.

A segmentation scheme based upon physical processes such as circulation and salinity should track very well with the major chemical and biological processes. However, after developing a network based upon physical characteristics, segment boundaries can be refined with available chemical and biological data to maximize the homogeneity of each segment.

To illustrate the segmentation approach to evaluating relationships between physical characteristics and use attainability, the segmentation scheme applied to Chesapeake Bay is described below. While most of the estuaries subjected to use attainability evaluations will be considerably smaller and less diverse than Chesapeake Bay, the principles illustrated in the following example can serve as useful guidance for most estuary evaluations regardless of the spatial scale. Figure II-7 shows the main stem and tributary segments defined for Chesapeake Bay by the U.S. Environmental Protection Agency's Chesapeake Bay Program (U.S. EPA Chesapeake Bay Program 1982). As may be seen, the segment network consists of eight main stem segments designated by the prefix "CB" and approximately forty segments covering major embayments and tributaries. The methodology for delineating the main stem segments will be described first, followed by a discussion of the major embayments and tributaries.

Starting at the uppermost segment and working down the main stem, the boundary between CB-1 and CB-2 separates the mouth of the Susquehanna River from the upper Bay and lies in the region of maximum penetration of saltwater at the head of the Bay. South of this region most freshwater plankton would not be expected to grow and flourish, although some may be continually brought into the area by the Susquehanna River.

The boundary between CB-2 and CB-3 is the southern limit of the turbidity maximum, a region where suspended sediment causes light limitation of phytoplankton production most of the year. This boundary also coincides with the long-term summer average for the 5 parts per thousand (ppt) salinity contour which is an important physiological parameter for oysters.

The boundary between CB-3 and CB-4 is located at the Chesapeake Bay Bridge. It marks the northern limit of the 10 ppt salinity contour and of deep water anaerobic conditions in Chesapeake Bay stratification. In segment

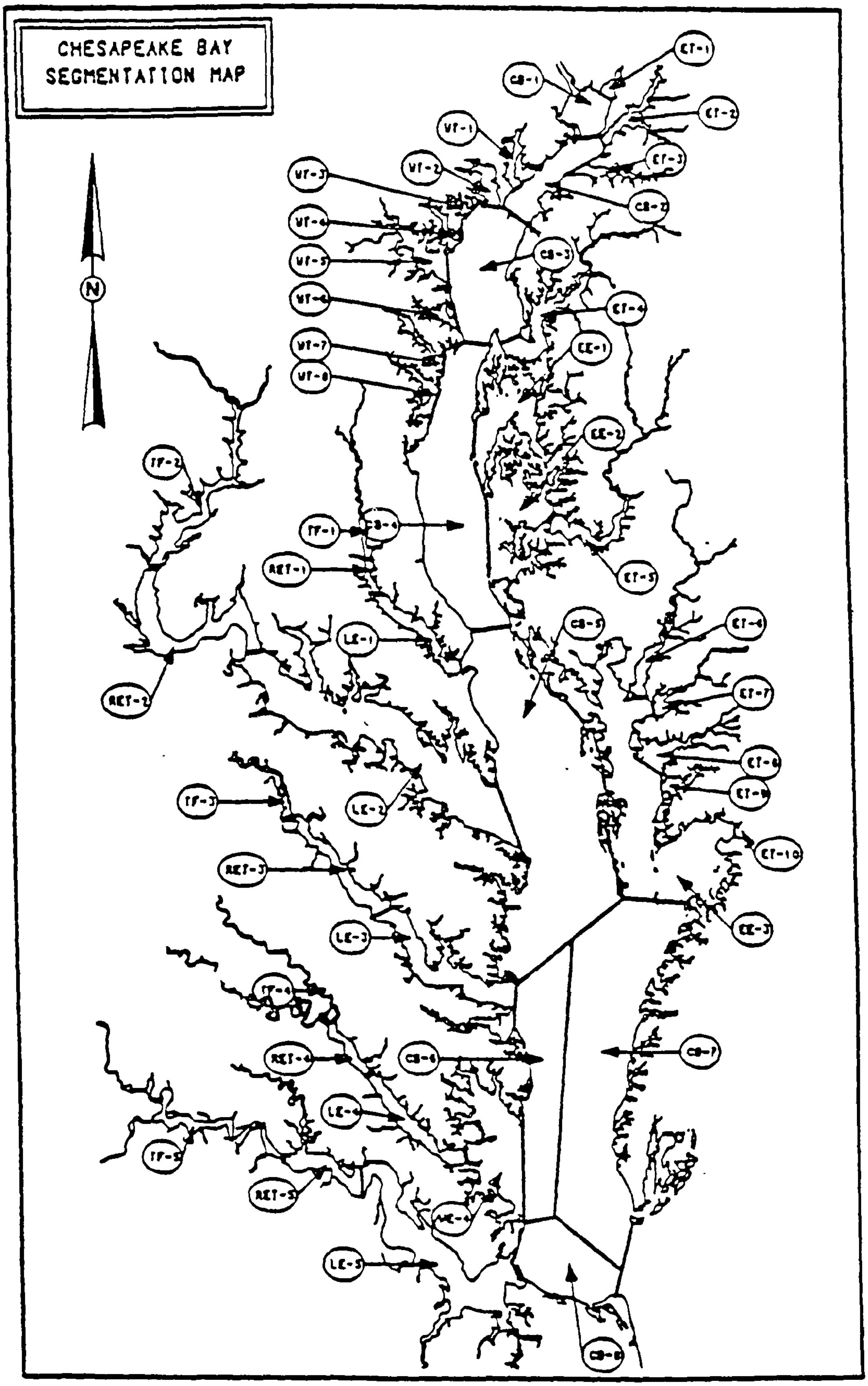


Figure II-7. Chesapeake Bay Program segments used in data analysis.(from U.S.EPA Chesapeake Bay Program 1982)

CB-4, water deeper than about 30 ft usually experiences oxygen depletion in summer which may result in oxygenless conditions and hydrogen sulfide production. When anaerobic conditions occur, these deep waters are toxic to fish, crabs, shellfish, and other benthic animals. Due to the increased release of nutrients from bottom sediments under oxygenless conditions, the anaerobic layer is also rich in phosphorus and ammonia-N which may reach surface waters by diffusion, mixing, and vertical advection either later in the year or in less stratified sections of the Bay. In spring, the region near the bridge is the site where phytoplankton and fish larvae that travel in the deep layer from the Bay mouth are brought to the surface by a combination of physical processes.

The boundary between CB-4 and CB-5 was established at a narrows. Below this point, the Patuxent and Potomac Rivers intersect the main stem of the Bay. It is characterized by average summer salinities of 12 to 13 ppt and is located at the approximate midpoint of the area subject to bottom water anaerobic conditions during the summer.

The boundary between CB-5 and CB-6/7 approximates the 18 ppt salinity contour and the southern limit of significant vertical stratification and anaerobic conditions in the bottom waters. Most of the deeper areas of the Bay are found in segment CB-5. As mentioned earlier, the bottom waters of segments CB-4 and CB-5 experience considerable nutrient enrichment during the summer when phosphorus and ammonia-N are released from bottom sediments. This region also exhibits high nitrate-N concentrations in the fall when the ammonia-N accumulated in summer is oxidized. The southern boundary of CB-5 also approximates the region where the elevated nitrate-N concentrations from the relatively high streamflows during the spring season becomes a critical factor in phytoplankton growth.

The boundary between CB-6 and CB-7 horizontally divides the lower Bay into two regions with different circulation patterns. North of this boundary, the Bay's density stratification results in two distinct vertical layers, with bottom waters moving in a net upstream flow and the surface layer flows moving downstream. Between this boundary and the Bay mouth the density distribution tends toward a cross-stream (i.e., horizontal) gradient rather than a vertical gradient. Net advective flows throughout a vertically well-mixed water column tend to flow northward in segment CB-7 and southward in CB-6 and CB-8. This pronounced horizontal gradient also exists across the Bay mouth. Thus, plankton and fish larvae are brought into the Bay with the higher salinity ocean waters along the eastern side of the lower Bay until they become entrained into the lower layer at segment CB-5 and are transported up the Bay to grow and mature.

Eastern shore embayments such as Eastern Bay (EE-1), the subestuary of the Choptank River (EE-2) and the Pocomoke and Tangier Sounds (EE-3) have salinities similar to adjacent Bay waters, and they are shallow enough to permit light penetration necessary for the growth of submerged aquatic vegetation (SAVs). These areas provide shelter for many benthic invertebrates and small fish which make an important contribution to the Bay's rich environment.

Boundaries have been delineated at the mouths of the Bay's major tributaries. These boundaries define the sources of freshwater, sediment, nutrients, and other constituents delivered to the main stem of the Bay. Along these boundaries, frontal zones between the tributary and main stem waters tend to concentrate detrital matter and nutrients, with circulation patterns governing the transport of many organisms to this food source.

The major tributaries are further subdivided into three segment classifications: tidal fresh (TF), river estuarine transition zone (RET), and lower subestuary (LE). The tidal fresh segments are biologically important as spawning areas for anadromous and semianadromous fish such as the alewife, herrings, shad, striped bass, white perch and yellow perch. There are also freshwater species which are resident in these areas such as catfish, minnows and carps. Algal blooms tend to be most prolific within the tidal fresh zone. The extent of these blooms is dependent upon nutrient supply, a range of factors such as retention time, and light availability. Most of the algal species that can flourish within tidal fresh segments are inhibited as they encounter the more saline waters associated with the transition zone.

The highest concentration of suspended solids is found at the interface of fresh and saline waters and it approximates the terminus of density dependent estuarine circulation. The area where this phenomenon occurs is typically referred to as the "turbidity maximum" zone. The significance of this area lies in its value as a sediment trap entraining not only material introduced upstream but, additionally, material transported in bottom waters from downstream. This mechanism also tends to concentrate any material associated with the entrained sediment. For example, Kepone accumulations within the James River estuary are highest in the turbidity maximum zone.

The final segment type found within the major tributaries is identified as the lower subestuary segment. This area extends from the turbidity maximum to the point where the tributary intersects the main stem of the Bay. Highly productive oyster bars are found in these segments. There is a heavy concentration of oyster bars in the lower subestuaries because of the favorable depth, salinities, and substrate. In general, the oyster bars are located in depths of less than 35 feet in salinities greater than 7-8 ppt and on substrates which are firm. Seasonal depressions of dissolved oxygen in bottom waters prevent the establishment of oyster bars in most waters over 35 feet deep.

CHEMICAL PARAMETERS

This section provides a brief discussion of chemical indicators of aquatic use attainment for estuaries. Three clarifications are necessary before beginning this discussion. First, while it is useful to refer to these parameters as "chemical" characteristics to distinguish them from the physical and biological parameters in a use attainability evaluation, these characteristics are traditionally referred to as water quality criteria and are referred to as such in other sections of this report. Second, chlorophyll-a is introduced in this section rather than in Chapter III because it is the primary impact indicator for chemicals such as nitrogen and phosphorus. Third, because an extensive discussion of chemical water quality indicators is presented in the earlier U.S. EPA Technical Support Manual (U.S. EPA November 1983), the discussion herein is very limited. Manual users who are interested in a more extensive discussion are referred to the previous volume.

The most critical water quality indicators for aquatic use attainment in an estuary are dissolved oxygen, nutrients and chlorophyll-a, and toxicants. Dissolved oxygen (DO) is an important water quality indicator for all fisheries uses. The DO concentration in bottom waters is the most critical indicator of survival and/or density and diversity for most shellfish and an important indicator for finfish. DO concentrations at mid-depth and surface locations are also important indicators for finfish. In evaluating use attainability, assessments of DO impacts should consider the relative contributions of three different sources of oxygen demand: (a) photosynthesis/respiration demand from phytoplankton; (b) water column demand; and (c) benthic oxygen demand. If use impairment is occurring, assessments of the significance of each oxygen sink can be used to evaluate the feasibility of achieving sufficient pollution control to attain the designated use.

Chlorophyll-a is the most popular indicator of algal concentrations and nutrient overenrichment which in turn can be related to diurnal DO depressions due to algal respiration. Typically, the control of phosphorus levels can limit algal growth in the upper end of the estuary, while the control of nitrogen levels can limit algal growth near the mouth of the estuary; however, these relationships are dependent upon factors such as N:P ratios and light penetration potential which can vary from one estuary to the next, thereby producing different limiting conditions within a given estuary. Excessive phytoplankton concentrations, as indicated by chlorophyll-a levels, can cause adverse DO impacts such as: (a) wide diurnal variations in surface DO's due to daytime photosynthetic oxygen production and nighttime oxygen depletion by respiration, and (b) depletion of bottom DO's through the decomposition of dead algae. Thus, excessive chlorophyll-a levels can deplete the oxygen resources required for bottom water fisheries, exert stress on the oxygen resources of surface water fisheries, and upset the balance of the detrital foodweb in the seagrass community through the production of excessive organic matter.

Excessive chlorophyll-a levels also result in shading which reduces light penetration for submerged aquatic vegetation. Consequently, the prevention of nutrient overenrichment is probably the most important water quality requirement for a healthy SAV community.

Blooms of certain phytoplankton can also be toxic to fish. For example, blooms of the toxic "red tide" organism during the early 1970's resulted in extensive fish kills in several Florida estuaries.

The nutrients of concern in the estuary are nitrogen and phosphorus. Their sources typically are discharges from sewage treatment plants and industries, and runoff from urban and agricultural areas. Increased nutrient levels lead to phytoplankton blooms and a subsequent reduction in DO levels, as discussed above. In addition, algal blooms decrease the depth to which light is able to penetrate, thereby affecting SAV populations in the estuary.

Sewage treatment plants are typically the major source of nutrients to estuaries in urbanized areas. Agricultural land uses and urban land uses represent significant nonpoint sources of nutrients. Often wastewater treatment plants are the major source of phosphorus loadings while nonpoint sources tend to be major contributors of nitrogen. In estuaries located near highly urbanized areas, municipal discharges probably will dominate the point source nutrient contributions. Thus, it is important to base control strategies on an understanding of the sources of each type of nutrient, both in the estuary and in its feeder streams.

In the Chesapeake Bay, an assessment of total nitrogen, total phosphorus, and N:P ratios indicates that regions where resource quality is currently moderate to good have lower concentrations of ambient nutrients, and N:P ratios between 10:1 and 20:1, indicating phosphorus-limited algal growth. Regions characterized by little or no SAV's (i.e., phytoplankton-dominated systems) or massive algal blooms had high nutrient concentrations and significant variations in the N:P ratios. Moving a system from one class to another could involve either a reduction of the limiting nutrient (N or P) or a reduction of the non-limiting nutrient to a level such that it becomes limiting. For example, removal of P from a system characterized by massive algal blooms could force it to become a more desirable phytoplankton-dominated system with a higher N:P ratio.

Clearly the levels of both nitrogen and phosphorus are important determinants of the uses that can be attained in an estuary. Because point sources of nutrients are typically much more amenable to control than nonpoint sources, and because nutrient (phosphorus) removal for municipal wastewater discharges is typically less expensive than nitrogen removal operations, the control of phosphorus discharges is often the method of choice for the prevention or reversal of use impairment in the upper estuary (i.e., tidal fresh zone). However, the nutrient control programs for the upper estuary can have an adverse effect on phytoplankton growth in the lower estuary (i.e., near the mouth) where nitrogen is typically the critical nutrient for eutrophication control. This is because the reduction of phytoplankton concentrations in the upper estuary will reduce the uptake and settling of the non-limiting nutrient which is typically nitrogen, thereby resulting in increased transport of nitrogen through the upper estuary to the lower estuary where it is the limiting nutrient for algal growth. The result is that reductions in algal blooms within the upper estuary due to the control of one nutrient (phosphorus) can result in increased phytoplankton concentrations in the lower estuary due to higher levels of the uncontrolled nutrient (nitrogen). Thus, tradeoffs between nutrient controls for the upper and lower estuary should be considered in evaluating measures for preventing or reversing use impairment. The Potomac Estuary is a good example of a system where tradeoffs between nutrient controls for the upper and lower estuary are being evaluated.

The impacts of toxicants such as pesticides, herbicides, heavy metals and chlorinated effluents are beyond the scope of this volume. However, the presence of certain toxicants in excessive concentrations within bottom sediments or the water column may prevent the attainment of water uses (particularly fisheries propagation/harvesting and seagrass habitat uses) in estuary segments which satisfy water quality criteria for DO, chlorophyll-a/nutrient enrichment, and fecal coliforms. Therefore, potential interferences from toxic substances need also to be considered in a use attainability study.

TECHNIQUES FOR USE ATTAINABILITY EVALUATIONS

Introduction

Use attainability evaluations generally follow the conceptual outline:

- o Determine the present use of the estuary,
- o Determine whether the present use corresponds to the designated use,
- o If the present use does not correspond to the designated use, determine why, and
- o Determine the optimal use for the system.

In assessing use levels for aquatic life protection, the first two items are evaluated in terms of biological measurements and indices. However, if the present use does not correspond to the designated use, one turns to physical and chemical factors to explain the lack of attainment, and the highest level the system can achieve.

The physical and chemical evaluations may proceed on several levels depending on the level of detail required, amount of knowledge available about the system (and similar systems), and budget for the use- attainability study. As a first step, the estuary is classified in terms of physical processes (e.g., stratification, flushing time) so that it can be compared with reference estuaries that exhibit similar physical characteristics. Once a similar estuary is identified, it can be compared with the estuary of interest in terms of water quality differences and differences in biological communities which can be related to man-made alteration (i.e., pollution discharges). It is important to consider a number of simplifying assumptions that can be made to reduce the conceptual complexity of the prototype system for easier classification and more detailed analyses.

The second step is to perform desk-top or simple computer model calculations to improve the understanding of spatial and temporal water quality conditions in the present system. These calculations include continuous point source and simple box model type calculations, among others.

The third step is to perform more detailed analyses to investigate system impact from known anthropogenic sources through the use of more sophisticated computer models. These tools can be used to evaluate the system response to removing individual point and nonpoint source discharges, so as to assist with assessments of the cause(s) of any use impairment.

Desktop Evaluations of System Characteristics

This section discusses desktop analyses for evaluating relationships between physical/chemical characteristics and use attainability. Desktop evaluations that can provide guidance for the selection of appropriate mathematical models for use attainability studies are also discussed.

Such evaluations can be used to characterize the complexity of an estuary, important physical characteristics such as the level of vertical stratification and flushing times, and violations of water quality criteria. Depending upon the complexity of the estuary, these evaluations can quantify the temporal and spatial dimensions of important physical/chemical characteristics and relationships to use attainability needs as summarized below:

1. Vertical Stratification

   a. Temporal Scale: During which seasons does it occur? What is the approximate duration of stratification in each season?

   b. Spatial Scale: How much area is subject to significant stratification in each season?

2. Flushing Times

   a. Temporal Scale: What are the flushing times for each major estuary segment and the estuary as a whole?

   b. Spatial Scale: Which segments exhibit relatively high flushing times? Relatively low flushing times?

3. Violations of Water Quality Criteria (based upon statistical analysis of measured data)

   a. Temporal Scale: Which seasons exhibit violations? How frequently and for what durations do violations occur in each season? Are the violations caused by short-term or long-term phenomena? Short-term phenomena include: DO sags due to combined sewer overflows or short-term nonpoint source loadings, and diurnal DO variations due to significant chlorophyll-a levels. Long-term phenomena include: seasonal eutrophication impacts due to nutrient loadings, seasonal DO sag due to point source discharges, and seasonal occurrence of anaerobic conditions in bottom waters due to persistent vertical stratification.

   b. Spatial Scale: What is the spatial extent of the violations (considering longitudinal, horizontal, and vertical directions)?

4. Relationship of Physical/Chemical Characteristics to Use Attainability Needs

a. Temporal Scale: Are use designations more stringent during certain seasons (e.g., spawning season)? Are acceptable physical/chemical characteristics required 100 percent of the time in each season in order to ensure use attainability?

b. Spatial Scale: Are there segments in the estuary which cannot support designated uses due to physical limitations? Are acceptable physical/chemical characteristics required in 100 percent of the estuary segment or estuary in order to ensure attainability of the use?

Simplifying Assumptions. Zison et al. (1977) and Mills et al. (1982) list a number of simplifying assumptions that can be made to reduce the complexity of estuary evaluations. However, care must be taken to ensure that such assumptions are applicable to the estuary under study and that they do not reduce the problem to one which is physically or chemically unreasonable. The following assumptions may be considered (Zison et al., 1977; Mills et al., 1982):

a. The present salinity distribution can be used as a direct measure of the distribution of all conservative continuous flow pollutants entering the estuary, and can be used as the basis for calculating dispersion coefficients for a defined freshwater discharge condition,

b. The vertical water column is assumed to be well mixed from top to bottom,

c. Flow and transport through the estuary is essentially one-dimensional,

d. The Coriolis effect may be neglected, which means that the estuary is assumed to be laterally homogeneous,

e. Only steady-state conditions will be considered, by using calculations averaged over one or more tidal cycles to estimate a freshwater driven flow within the estuary,

f. Regular geometry may be assumed, at least over the length of each segment, which means that topographically induced circulations are neglected,

g. Only one river inflow can be used in the evaluation,

h. No variations in tidal amplitude are permitted, and

i. All water leaving the estuary on each tidal cycle is replaced by a given percentage of "fresh" seawater.

The above list of assumptions are directed towards the specific objective of reducing the estuary to a one-dimensional, quasi-steady-state system amenable to desktop calculations. In reality these assumptions need to be carefully weighed so that important processes are not omitted from the analysis.

One approach is to start with a completely three-dimensional system, determine which assumptions can reasonably be made, and see what the answer means in terms of a simplified analysis. Procedures for making such determinations are discussed in the next section, but several examples are presented here for illustration.

The fact is that many narrow estuarine systems in which lateral homogeneity can be assumed, also exhibit 2 or more layers of residual flow, making the assumption of a one-dimensional system invalid. Conversely, given a vertically well-mixed system like Biscayne Bay, one cannot assume lateral homogeneity because the system is usually very wide wind mixing is too significant to permit such a simple analysis.

Degree of Stratification.

Freshwater is lighter than saltwater. Therefore, the river may be thought of as a source of buoyancy, of amount:

$$\text{Buoyancy} = \Delta\rho g Q_f \tag{1}$$

where
$\Delta\rho$ = the difference in density between sea and river water, M/L^3
g = acceleration of gravity, L/T^2
Q_f = freshwater river flow, L^3/T
M = units of mass
L = units of length
T = units of time

The tide on the other hand is a source of kinetic energy, equal to:

$$\text{kinetic energy} = \rho W U_t^3 \tag{2}$$

where
ρ = the seawater density,
W = the estuary width
U_t = the square root of the averaged squared velocities.

The ratio of the above two quantities, called the "Estuarine Richardson Number" (Fischer 1972), is an estuary characterization parameter which is indicative of the vertical mixing potential of the estuary:

$$R = \frac{g\,Q_f}{W U_t^3} \tag{3}$$

If R is very large (above 0.8), the estuary is typically considered to be strongly stratified and the flow to be typically dominated by density currents. If R is very small, the estuary is typically considered to be well-mixed and the density effects to be negligible.

Another desktop approach to characterizing the degree of stratification in the estuary is to use a stratification-circulation diagram (Hansen and Rattray 1966). The diagram (shown in Figure II-8) requires the calculation of two parameters:

$$\text{Stratification Parameter} = \frac{\Delta S}{S_o} \qquad (4)$$

$$\text{and Circulation Parameter} = \frac{U_s}{U_f}$$

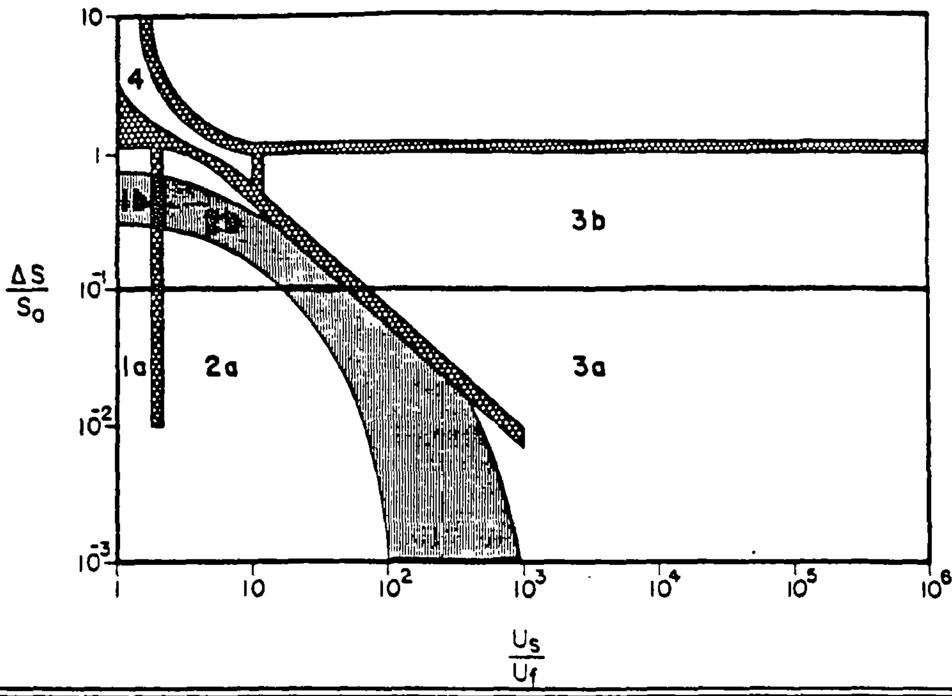
where

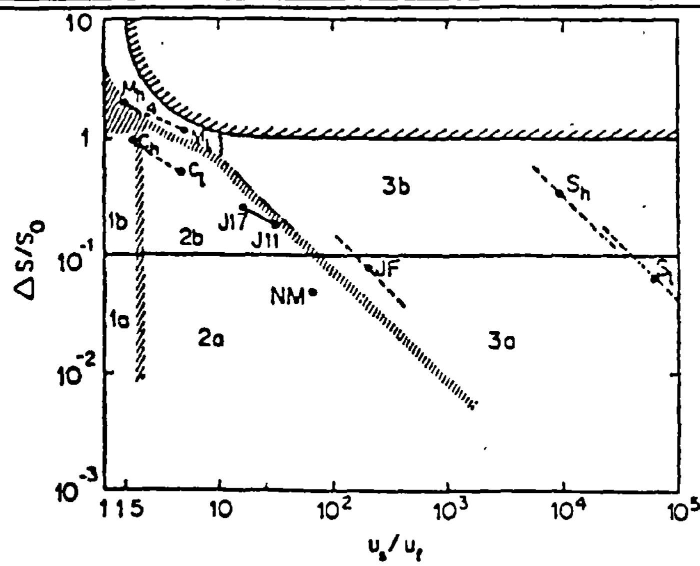
ΔS = time averaged difference between salinity levels at the surface and bottom of the estuary,
S_o = cross-sectional mean salinity,
U_s = net non-tidal surface velocity, and
U_f = mean freshwater velocity through the section.

To apply the stratification-circulation diagram in Figure II-8, which is based on measurements from a number of estuaries with known degrees of stratification, calculate the parameters of Equation (4) and plot the resulting point on the diagram. Type 1a represents slight stratification as in a laterally homogeneous, well-mixed estuary. In Type 1b, there is strong stratification. Type 2 is partially well-mixed and shows flow reversals with depth. In Type 3a the transfer is primarily advective, and in Type 3b the lower layer is so deep, as in a fjord, that circulation does not extend to the bottom. Finally, Type 4 represents the salt-wedge type with intense stratification (Dyer 1973).

The purpose of the analysis is to examine the degree of vertical resolution needed for the analysis. If the estuary is well-mixed, the vertical dimension may be neglected, and all constituents in the water column assumed to be dispersed evenly throughout. If the estuary is highly stratified, at least a 2-layer analysis must follow. For the case of a partially-mixed system, a judgment call must be made. The James River may be considered as an example which is partially stratified but was treated as a 2-layer system for a recent toxics study (O'Connor, et al., 1983).

A final desktop method for characterizing the degree of stratification is the calculation of the estuary number proposed by Thatcher and Harleman (1972):





(Station code: M, Mississippi River mouth; C, Columbia River estuary; J, James River estuary; NM, Narrows of the Mersey estuary; JF, Strait of Juan de Fuca; S, Silver Bay. Subscripts h and l refer to high and low river discharge; numbers indicate distance (in miles) from mouth of the James River estuary.

Figure II-8. Stratification Circulation Diagram and Examples.

$$E_d = \frac{P_t F_d^2}{Q_f T} \qquad (5)$$

where
E_d = estuary number,
P_t = tidal prism volume (volume between low and high tides),
Q_f = freshwater inflow,
T = tidal period, and
F_d = densimetric Froude number =

$$\frac{U_1}{\left(g\left(\frac{\Delta\rho}{\rho_1}\right)h_1\right)^{\frac{1}{2}}}$$

where
U_1 = layer velocity,
g = acceleration due to gravity,
$\Delta\rho$ = density difference across interface,
ρ_1 = density in layer, and
h_1 = layer thickness.

Again, by comparing the calculated value with the values from known systems, one can infer the degree of stratification present. The reader should consult Thatcher and Harleman (1972) for further details.

Horizontal variations in density may still exist in a vertically well-mixed estuary, resulting in circulation that is density driven in the horizontal direction. It is helpful to understand density-driven circulation in an estuary (baroclinic circulation) in order to assess its effect in relation to turbulent diffusion on the landward transport of salinity. While numerous studies have been performed over the years (e.g., Hansen and Rattray 1965, 1966; Rigter, 1973), no unifying theory has emerged clearly delineating longitudinal, transverse and vertical dispersion mechanisms. This means that we still have to rely to a large extent on actual in-situ data.

Decisions about whether it is reasonable to neglect processes such as Coriolis effects and wind is often judgmental. However, Cheng (1977) did offer the following criterion for neglecting the Coriolis effect. The criterion is based on the Rossby number:

$$R_o = \frac{\Omega \bar{u}}{L} \qquad (6)$$

where R_o = Rossby number,
$\overline{u}$ = characteristic wind velocity = 1/2 peak surface velocity,
Ω = earth's rotation rate, and
L = length of estuary,

Cheng suggested that for $R_o < 0.1$, the Coriolis effect is small. Wind is so highly variable and unpredictable that it is almost always neglected. In general, it has little effect on steady-state conditions, except in large open estuaries.

Finally, the use of simplified geometries, such as uniform depth and width is highly judgmental. One may choose to neglect side embayments, minor tributaries, narrows and inlets as a symplifying approach to achieve uniform geometry. However, it is always important to consider the consequences of this assumption.

Flushing Time. The time that is required to remove pollutant mass from a particular point in an estuary (usually some upstream location) is called the flushing time. Long flushing times are often indicative of poor water quality conditions due to long residence times for pollutants. Flushing time, particularly in a segmented estuary, can also be used in an initial screening of alternate locations for facilities which discharge constituents detrimental to estuarine health if they persist in the water column for lengthy periods.

Factors influencing flushing times are tidal ranges, freshwater inflows, and wind. All of these forcing functions vary over time, and may be somewhat unpredictable (e.g., wind). Thus, flushing time calculations are usually based on average conditions of tidal range and freshwater inflows, with wind effects neglected.

The Fraction of Fresh Water Method for flushing time calculation is based upon observations of estuarine salinities:

$$F = \frac{S_o - S_e}{S_e} \quad . \tag{7}$$

where F = flushing time in tidal cycles,
S_o = salinity of ocean water, and
S_e = mean estuarine salinity.

The tidal prism method for flushing time calculation considers the system as one unit with tidal exchange being the dominant process:

$$F = \frac{V_L + P}{P} \quad (8)$$

where F = flushing time in tidal cycles,
V_L = low tide volume of the estuary, and
P = tidal prism volume (volume between low and high tides).

The Tidal Prism technique was further modified by Ketchum (1951) to segment the estuary into lengths defined by the maximum excursion of a particle of water during a tidal cycle. This technique can now include a freshwater inflow:

$$F = \sum_{i=1}^{n} \frac{V_{Li} + P_i}{P_i} \quad (9)$$

where F = flushing time in tidal cycles,
i = segment number,
n = number of segments
V_{Li} = low tide volume in segment i, and
P_i = tidal prism volume in segment.

Riverine inflow is accounted for by setting the upstream length equal to the river velocity multiplied by the tidal period, and setting:

$$P_o = Q_f T \quad (10)$$

where P_o = tidal prism volume in upstream segment,
Q_f = freshwater flow, and
T = tidal period.

Finally, the replacement time technique is based upon estuarine geometry and longitudinal dispersion:

$$t_R = 0.4\, L^2/E_L \quad (11)$$

where t_R = replacement time,
L = length of estuary, and
E_L = longitudinal dispersion coefficient.

This technique requires knowledge of a longitudinal dispersion coefficient, E_L, which may not be known from direct estuarine measurements. A coefficient based upon measured data from a similar estuary may be assumed (see Table II-4 for typical values in a number of U.S. estuaries) or it may be estimated from empirical relationships, such as the one reported by Harleman (1964):

$$E_L = 77\ n\ u\ R^{5/6} \tag{12}$$

or Harleman (1971):

$$E_L = 100\ n\ u_{max}\ R^{5/6} \tag{13}$$

where E_L = longitudinal dispersion coefficient (ft^2/sec),
n = Manning's roughness coefficient (0.028-0.035, typically),
u = velocity (ft/sec),
u_{max} = maximum tidal velocity, and
R = hydraulic radius = A/P

where A = cross sectional area,
P = wetted perimeter.

Desktop Calculations of Pollutant Concentrations

Classification and characterization are means of identifying estuarine types and their major processes as a basis for comparison with reference estuaries. There are some desktop methods for calculating ambient water quality for defined pollutant loading conditions which can provide further insight into system response for use attainability evaluations.

These techniques usually assume uniform geometry, a well-mixed system, and net freshwater driven flows. There are essentially two types of desktop calculations for ambient water quality evaluations -- mixed tank analyses and simple analytic solutions to the governing equations.

Under the first approach, the pollutant discharge is continuously mixed with an inflowing river, or else at a point along the estuary. Solutions at steady-state are well-known (Mills et al., 1982). For a river borne pollutant inflow, the steady-state concentration for a conservative pollutant may be calculated as follows:

$$C_{pi} = \frac{T_i\ Q_f}{V} \tag{14}$$

TABLE II-4

OBSERVED LONGITUDINAL DISPERSION COEFFICIENTS

Estuary	River Flow	Dispersion Coefficents	
	(cfs)	(m^2/sec)	(ft^2/sec)
Delaware River (DE/NJ)	2500	150	1600
Hudson River (NY)	5000	600	6500
East River (NY)	0	300	3250
Cooper River (SC)	10000	900	9700
Savannah River (GA, SC)	7000	300-600	3250-6500
Lower Raritan River (NJ)	150	150	1600
South River (NJ)	23	150	1600
Houston Ship Channel (TX)	900	800	8700
Cape Fear River (NC)	1000	60-300	650-3250
Potomac River (MD/VA)	550	30-300	325-3250
Compton Creek (NJ)	10	30	325
Wappinger and Fishkill Creek (NY)	2	15-30	160-325
San Francisco Bay (CA):			
Southern Arm	-	18-180	200-2000
Northern Arm	-	46-1800	500-20000

SOURCE: From Mills et al. (1982).

where C_{pi} = pollutant concentration in segment i,
T_i = flushing time for segment i,
Q_f = freshwater flow, and
V_i = water volume at segment i.

For a direct discharge along the estuary, the concentration of a conservative pollutant at any section downstream is given by (Dyer 1973):

$$C_x = \left(\frac{C_p\ Q_p\ f_x}{Q_f + Q_p}\right)\left(\frac{S_s - S_x}{S_s - S_o}\right) \tag{15}$$

and at a section upstream:

$$C_x = \left(\frac{C_p\ Q_p\ f_o}{Q_f + Q_p}\right)\left(\frac{S_x}{S_o}\right) \tag{16}$$

where C = concentration,
C_p = inflow concentration,
Q_p = inflow rate,
f_o = fraction of freshwater in segment,
Q_f = river flow,
S = salinity,
subscript x - denotes distance downstream,
subscript o - denotes point of injection, and
subscript s - denotes ocean salinity.

A refinement to the above desktop methods involve calculations for nonconservative pollutants. The usual approach is to rely upon a first order decay relationship:

$$C_t = C_o\ e^{-k_T t} \tag{17}$$

where C_t = concentration at time t,
C_o = initial concentration, and
k_T = decay or reaction rate at temperature T.

The decay rate, k, is often expressed as a function of water temperature, based upon the departure from a standard temperature (usually 20°C):

$$k_T = k_{20}\,\theta^{T-20} \tag{18}$$

where k_{20} = decay or reaction rate at 20°C, and
= constant (1.03-1.04).

The final pollutant concentration is then calculated by applying a first-order decay to the dilution concentration given from Equations (14)-(16), based on an estimate of travel time to the cross-section of interest.

The second approach is to greatly simplify the governing mass transport equation, and derive a closed-form solution which can be evaluated using a hand-held calculator, for continuous, discrete discharges of either conservative or non-conservative pollutants (Mills et al., 1982). From the basic simplified equation for a continuous discharge of a nonconservative pollutant:

$$u\frac{dc}{dx} = E_L \frac{d^2c}{dx^2} - kc \tag{19}$$

the following solution can be readily derived:

$$c_x = c_o \exp\left[\frac{ux}{2E_L}\left(1 \pm \left(1 + \frac{4kE_L}{u^2}\right)^{\frac{1}{2}}\right)\right] \tag{20}$$

where c_x = concentration at distance x (x is positive downstream, and negative upstream)
c_o = initial concentration,
u = mean velocity,
E_L = longitudinal dispersion coefficient, and
k = decay rate.

in the upstream and downstream directions, respectively. Again, dispersion coefficients, if not directly known, can be estimated from similar estuaries, or from empirical formulas, such as those given in Equations (12) and (13).

For multiple pollutant discharges, the resulting concentration curves for each source may be superimposed to give a final composite profile along the estuary (Figure II-9).

Finally, Equation (20) can be used to estimate the length of salinity intrusion by using salt as the constituent and assuming cross-sectional homogeneity and an ocean salinity of 35 ppt (Stommel 1953):

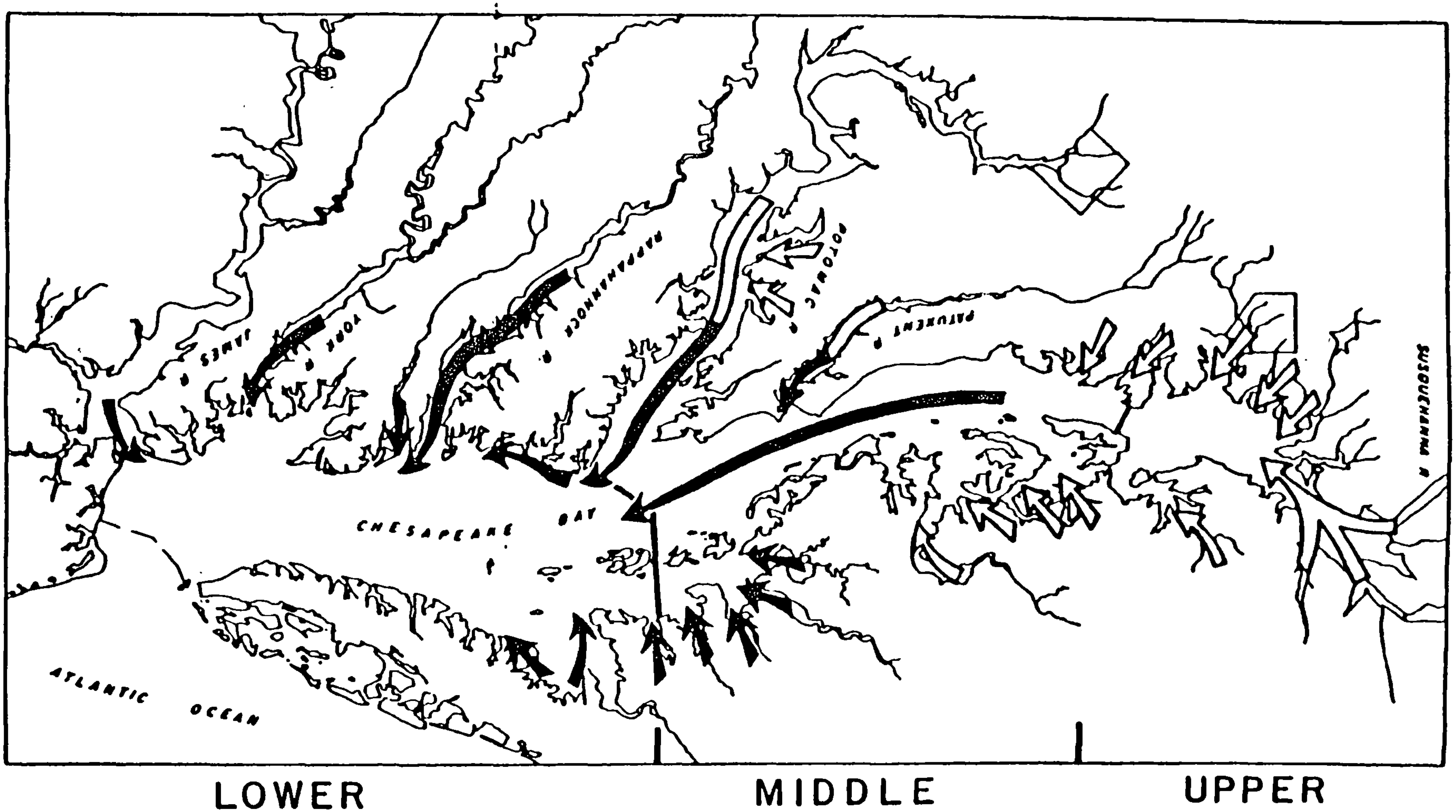


Figure II-9 Pattern of Recent Changes in the Distribution of Submerged Aquatic Vegetation (SAV) in the Chesapeake Bay: 1950-1980. Arrows Indicate Former to Present Limits. Solid Arrows Indicate Areas Where Eelgrass (Zostera Marina) Dominated. Open Arrows Indicate Other SAV Species.
(from U.S. EPA Chesapeake Bay Program, 1982)

$$x = \frac{3.5554\ A\ E_L}{Q_f} \tag{21}$$

where x = length of intrusion from ocean to 1 ppt isohaline,
A = cross-sectional area of estuary,
E_L = longitudinal dispersion coefficient, and
Q_f = freshwater inflow rate.

Such a desktop evaluation of salinity intrusion can be used to relate changes in freshwater inflow to use attainability within the upper estuary.

Other Desktop Evaluations for Use Attainability Assessments

The most common desktop evaluations of use attainability within estuaries are statistical analyses of water quality monitoring data to determine the frequency of violation of criteria for the designated aquatic use. Statistical evaluations of contraventions of water quality criteria should consider the confidence intervals for the number of violations that are attributable to random variations (rather than actual water quality deterioration). For example, consider an estuary monitoring station with 12 dissolved oxygen (DO) observations per year (i.e., a single slackwater sample each month) with a standard of 5 mg/l DO. If statistical analyses of the DO observations indicate that the upper and lower confidence limits for the frequency of random violations of the 5 mg/l DO standard cover a range of 1 to 4 violations per year, a regulatory agency should be cautious in deciding whether actual use impairment has occurred unless more than 4 violations are observed annually.

In addition to the State water quality standard values, both quantitative and qualitative measures should be considered for relationships between water quality criteria and use attainment. Quantitative measures include parametric statistical tests (i.e., assume normal frequency distribution) such as correlation analyses and simple and multiple regression analyses, as well as nonparametric statistical tests (i.e., distribution-free) such as the Spearman and Kendall correlation analysis. These quantitative tests might involve relating water quality indicators (e.g., DO, chlorophyll-a) to use attainability indicators such as juvenile index data (numbers per haul) for different finfish or commercial landings data (tons) for selected fisheries. Qualitative measures include graphical displays of historical trends in water quality and use attainment. For example, a map showing the areas which have experienced a decline in bottom DO conditions during the past 25 years could be overlaid on a map showing areas which experienced a decline in oyster beds over the same period. Another example, which proved to be very persuasive in the recent development of the U.S. EPA Chesapeake Bay management program (U.S. EPA Chesapeake Bay Program, 1982), is described in Figures II-9 through II-12. Figures II-9 and II-10 illustrate the decline in submerged aquatic vegetation (SAV) in Chesapeake Bay during the past three decades. Figures II-11 and II-12 illustrate changes in nutrient enrichment within Chesapeake Bay over the same period. The water quality index plotted in Figure II-12 is based on changes in the concentrations of both nitrogen and phosphorus. As may be seen, the areas of

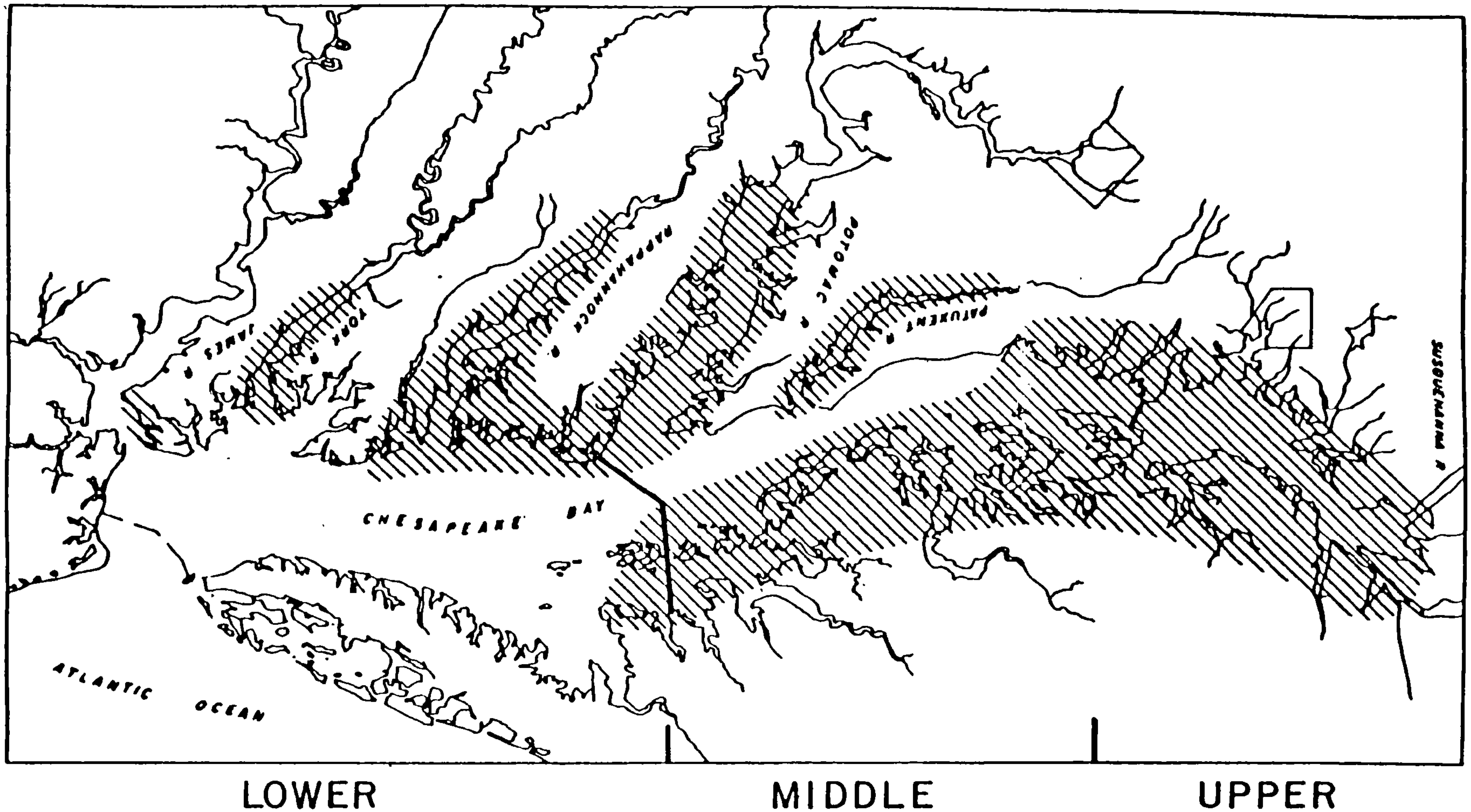


Figure II-10 Sections of Chesapeake Bay Where Submerged Aquatic Vegetation (SAV) has Experienced the Greatest Decline: 1950-1980 (from U.S. EPA Chesapeake Bay Program, 1982)

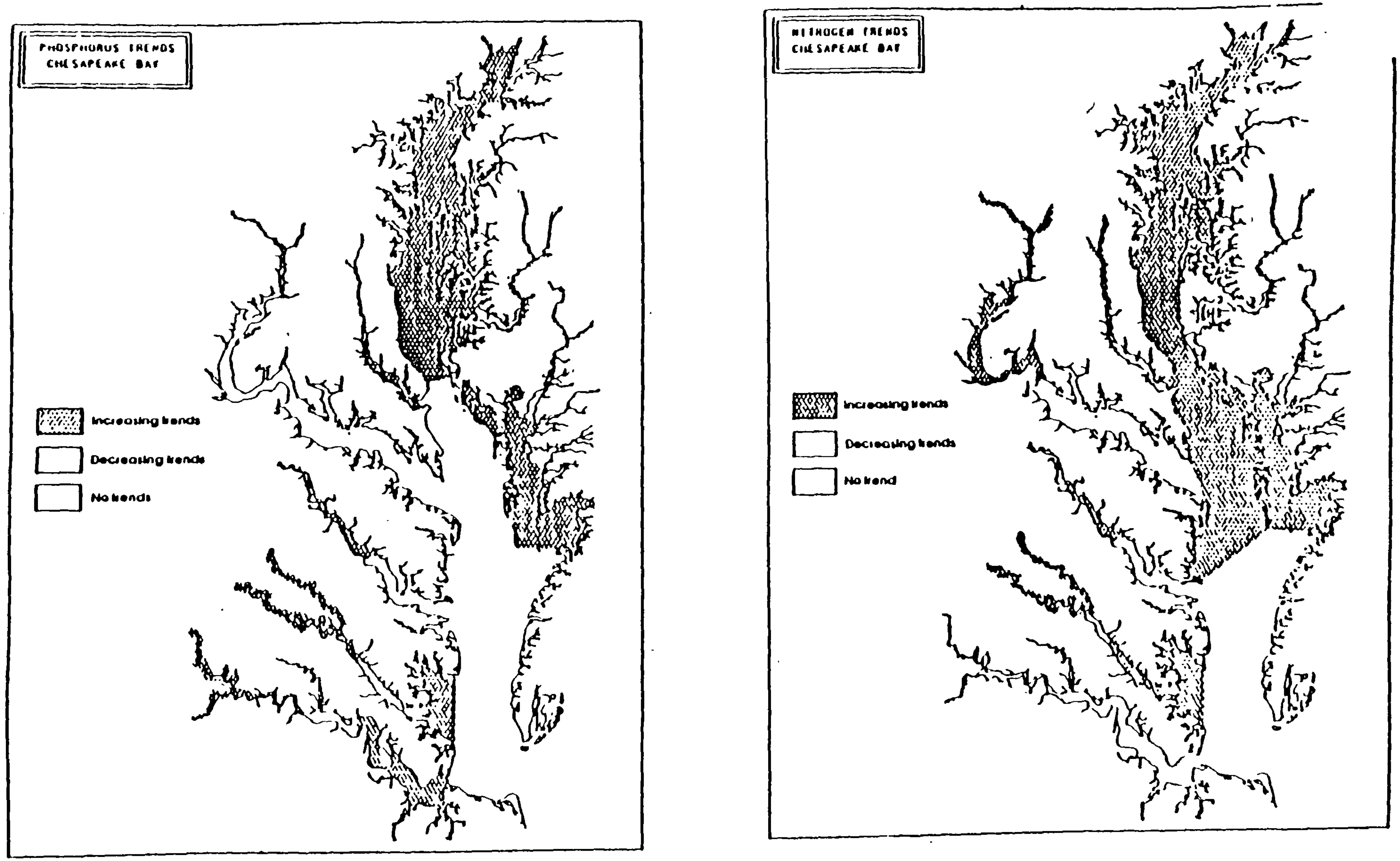


Figure II-11 Phosphorus and Nitrogen Trends in Chesapeake Bay: 1950-1980
(from U.S. EPA Chesapeake Bay Program, 1982)

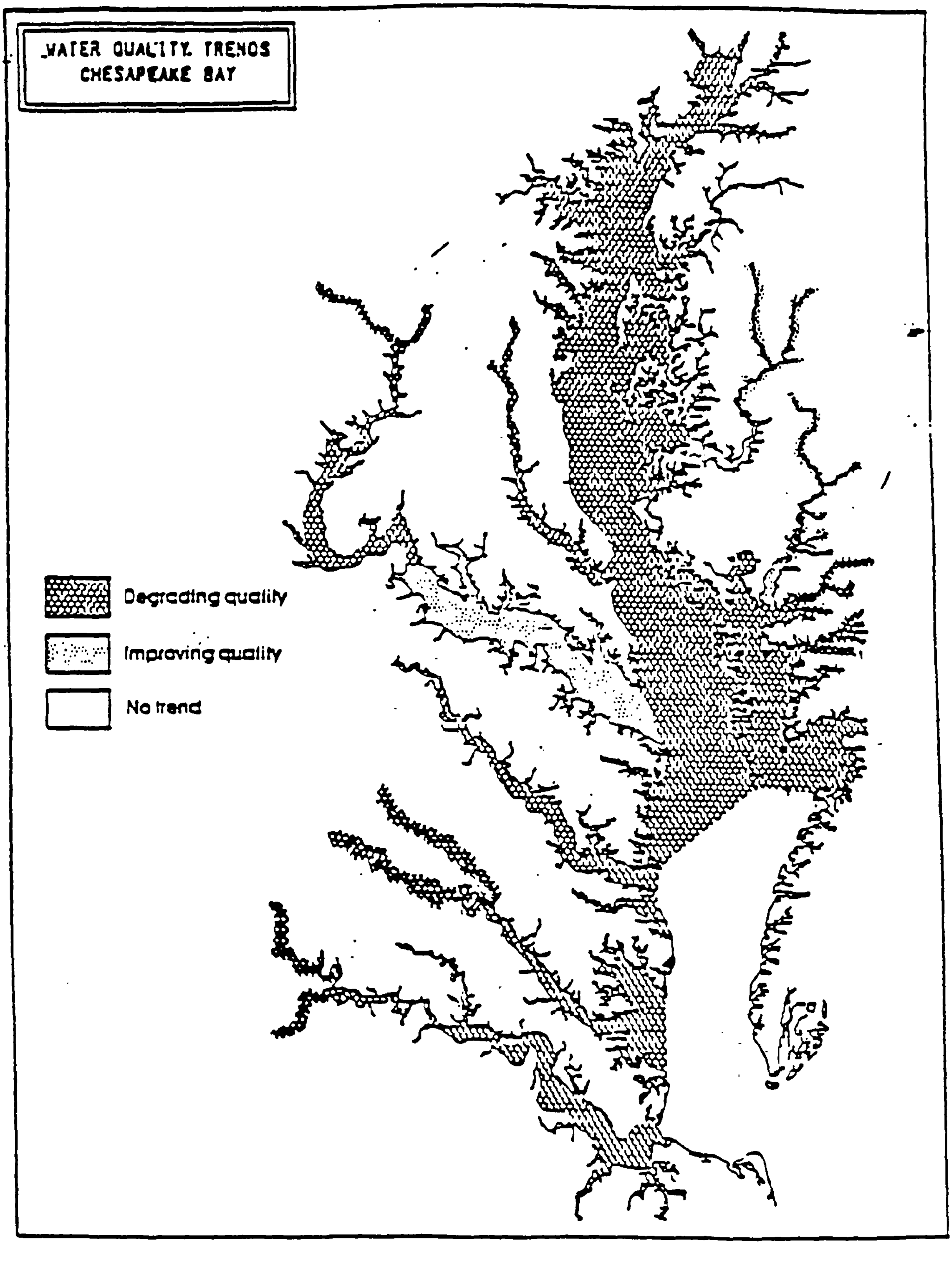


Figure II-12. Water Quality Trends in Chesapeake Bay. If either N or P trends (from Figure II-11) are increasing, then the overall water quality is said to be degrading.

"degrading quality" in Figure II-12 typically correspond to areas where submerged aquatic vegetation has experienced the greatest decline. Based on these types of qualitative comparisons and quantitative evaluations, the U.S. EPA Chesapeake Bay Program has secured considerable State, Federal, and Regional support for more aggressive water quality management efforts to protect Chesapeake Bay. Key to making decisions is the presentation of quantitative data as well as qualitative information.

In developing quantitative and qualitative measures for relationships between water quality and use attainability, care should be taken to distinguish the impacts of pollution discharges from the impacts of non-water quality factors such as physical alterations of the system. For example, in some estuaries, dredging/spoil disposal activities associated with the construction and maintenance of ship navigation channels and harbors may have contributed to use impairment over the years. Among the potential impacts of channel dredging is the reduction in the coverage of SAV's. Therefore, in order to minimize interferences from dredging/spoil disposal, analyses of water quality and use impairment for certain fisheries (e.g., shellfish) and SAV habitats should be based upon periods which do not include major dredging/spoil disposal operations. Another example of physical alterations which should be accounted for in any trend analyses is poor tidal flushing resulting from the construction of bridges and causeways. Potential contributions of extreme meteorologic conditions (e.g., hurricanes, air temperature) to use impairment should also be considered.

If it is determined that some estuary segments exhibit use attainment although violations of water quality criteria occur, the development of site-specific water quality criteria should be considered. Development of site-specific criteria is a method for taking unique local conditions into account. In the case of the water quality indicators (i.e., non-toxicants) being considered in this guidance manual, a potential application of site-specific criteria could be the establishment of temporal dimensions for water quality criteria to restrict use attainment requirements to certain seasons (i.e., in the event that year-round conformance with the water quality criteria is not required to protect the viability of the designated water use).

Computer Modeling Techniques for Use Attainability Evaluations

For many estuaries, field data on circulation, salinity, and chemical parameters may be inadequate for desktop evaluations of use attainability. In these cases, computer-based mathematical models can be used to expand the data base and define causal relationships for use attainability assessments. Specifically, there are three major areas in which computer models of estuaries can contribute to use attainability evaluations:

1. Applications of hydrodynamic and mass transport models can expand physical parameter data bases (i.e., circulation, salinity) in order to identify aquatic use segments and to determine whether physical characteristics are adequate for use attainment.

2. Applications of water quality models can expand chemical parameter (i.e., water quality) data bases in order to determine whether ambient water quality conditions are adequate for use attainment.

3. In cases where use impairment is noted despite acceptable physical characteristics, applications of water quality models can identify the causes of use impairment and alternative control measures that promise use attainment.

The major problem facing the engineer or scientist performing the evaluation is to select the most appropriate numerical model for a given study. Such a selection process must be based on a consideration of system geometry, physical and chemical processes of importance, and the temporal and spatial scales at which the evaluation is being conducted.

Previously discussed were some of the simplifications that can be made to reduce the conceptual complexity of an estuary from its inherently three-dimensional nature. Unfortunately, few quantitative measures exist to define precisely how such determinations should be made. Most criteria for selecting the most appropriate mathematical modeling approach are based on "intuitive judgment" or "experience" with few comparative indices, such as stratification diagrams and numbers, to make the selection less arbitrary.

One particular problem that needs to be addressed is the selection of steady-state versus dynamic approaches to estuarine modeling. Again, intuition leads one to accept that steady-state approaches are fine for rivers or river-flow dominated systems, such as the upper 50-miles of the Potomac River estuary near Washington, D.C. However, for areas further downstream in the estuary where the river flow is less dominant particularly in the dry season, one would intuitively consider using a dynamic approach. The question then is how to formulate a criterion for choosing between steady-state and dynamic modeling approaches. The governing parameters in the selection criteria might be expected to be some combination of freshwater inflow, tidal prism volume, density variations, and tidal period, perhaps in the form of the estuary number, E_D, given by Equation (7) or some other "number." A comparative study of various approaches at differing estuary numbers, E_D, might lead to an empirical formulation of a useful criterion for model selection, similar to the stratification diagram.

Once the appropriate simplifying assumptions have been made, the type of model needed can be determined. There are several model classifications that could be utilized for selection purposes. A four level scheme was used by Ambrose et al. (1981) to classify and compare a number of estuarine receiving water models. The recommended model classification scheme is as follows:

Level 1 - desktop methodologies,
Level 2 - steady-state or tidally averaged models
Level 3 - one-dimensional or quasi-two-dimensional real time models, and
Level 4 - two-dimensional or three-dimensional real time models.

Within each of the four levels, a number of numerical models are listed (Ambrose et al. 1981) and their utility for problem solving is discussed. In actuality, however, there are many more categories, which are subdivisions of the levels suggested by Ambrose et al. (1981). These are summarized in Table II-5 and discussed below, except Level 1 which was previously discussed.

Within Level 2, there are two subdivisions: one-dimensional steady-state models, and two-layer steady-state models. One-dimensional steady-state models assume that the hydraulics are driven entirely by a constant river inflow to the estuary or by net non-tidal (tidally averaged) flow. Conditions are assumed to be uniform over the cross-section, and the effects of Coriolis, wind, tidal, and stratification are neglected. Examples in this category are QUAL II (Roesner et al., 1981) and the WASP models (DiToro et al. 1981).

Two-layer (hydraulic) steady-state models are a simple, but fairly significant extension beyond the one-layer models, in that the advective transport can be resolved to allow for layered residual flow as in the James River. O'Connor et al. (1983) developed such a model to study the fate of Kepone in the James River, in which the net river flow could be specified in the top layer, and the net upstream density-driven flow specified in the lower hydraulic layer. In addition, this model has two sediment layers, one fluid and one fixed, with exchanges between all layers.

In Level 3, models can be subdivided into two categories: one-dimensional real time, and quasi-two-dimensional real time. The category of one-dimensional real-time models has an advantage over steady-state models in that the velocity field simulation can be completely dynamic, allowing tides, wind, friction, variable freshwater inflows, and longitudinal density variations to be included. Again, the estuary is assumed to be cross-sectionally homogeneous.

Quasi-two-dimensional real-time models are an improvement on the one-dimensional real-time representation in that they allow branching systems to be simulated. In addition, the link-node models (such as DEM and RECEIV) can be configured to approximate a two-dimensional horizontal geometry, thus allowing lateral variations to be included in the system evaluation. A very popular model in both these Level 3 categories is the Dynamic Estuary Model (DEM) which represents the geometry with a branching link-node network (Genet et al., 1974). This model is probably the most versatile of its kind and has been applied to numerous estuarine systems, bays, and harbors throughout the world. It contains a hydrodynamic program, DYNHYD, or DYNTRAN (Walton et al., 1983) in its density driven form, and a compatible water quality program, DYNQUAL, which can simulate up to 25 water quality constituents, including four trophic levels.

There are a variety of categories that might be considered in Level 4. Many two-dimensional, vertically-integrated, finite-difference hydrodynamic programs exist. There are, however, relatively few that contain a water quality program that simulates constituents other than salinity and/or temperature (Blumberg, 1975; Hamilton, 1975; Elliot, 1976). These are real time models, assuming only vertical homogeneity (Coriolis effects are now

TABLE II-5. CATEGORIES OF RECEIVING WATER MODELS

LEVEL	CATEGORY	INCLUDES	NEGLECTS	EXAMPLE MODELS
1	Desktop	Uniform flows	Wind, Coriolis, friction, tide Lateral and vertical variations	See text
2	1-D, steady-state	River flows Longitudinal variability	Wind, Coriolis, friction, tide Lateral and vertical variations	QUAL II WASP
2	2-layer, steady-state	River flows Residual upstream flows Longitudinal and vertical variability	Wind, Coriolis, friction, tides Lateral variations	O'Connor et al. (1983)
3	1-D real time	Tides, wind, river flows, friction Longitudinal variability	Coriolis Lateral and vertical effects	DEM RECEIV
3	Quasi 2-D real time	Tides, wind, river flows, friction Longitudinal and lateral variability	Coriolis, lateral momentum transfer Vertical variations	DEM RECEIV
4	2-D, finite-difference vertical integrated	Tides, wind, river flows, friction Coriolis Longitudinal and lateral variability	Vertical variations	Ross and Jerkins (1983)
4	2-D, finite-element vertically integrated	Tides, wind, river flows, friction Coriolis Longitudinal and lateral variability	Vertical variations	CAFE1/DISPER1 CBCM Chen (1978)
4	2-D, finite-difference laterally integrated	Tides, wind, river flow, friction Coriolis Longitudinal and vertical variability	Coriolis Lateral variations	CBCM
4	3-D	All physical processes	--	CBCM Leendertse et al. (1973)

included). An example of a water quality model in this category is the hydrodynamic and water quality model developed by Ross and Jerkins (1983) which has been extensively applied to Tampa Bay.

Similar to the above category are the two-dimensional, vertically-integrated, finite-element models. The physical process and simplifications are identical. The difference is that the geometry is represented as a series of elements (usually triangles) which can better represent complex coastlines. Examples of models in this category are the CAFE1/DISPER1 hydrodynamic models (Wang and Connor 1975; Leimkuhler 1974), the Chesapeake Bay Circulation Model, CBCM (Walton et al., 1983), and a water quality model developed by Chen (1978). The first two models can simulate only mass transport of a non-conservative constituent, whereas Chen's model is capable of representing most major water quality processes. CBCM has the additional advantages of a three-dimensional form and the capability to link 1-2 or 2-3-dimensional models to treat tributaries from a main bay or subgrid scale cuts in a main bay which cannot be resolved adequately at the horizontal spatial scale.

There are a number of two-dimensional, laterally-averaged models (longitudinal and vertical transport simulations) that treat mass transport of salt and temperature, but very few that include nonconservative constituents or water quality routines. While models in this category assume lateral homogeneity and neglect Coriolis effects, they can represent vertical stratification although for numerical reasons, care should be taken in defining vertical layers to represent the saltwater/freshwater interface of high stratified systems. The tributary submodels of CBCM (Walton et al., 1983) are included in this category.

Last is the category of three-dimensional, finite-difference and finite-element models. These models allow all physical processes to be included, although many were developed for systems of constant salinity (lakes or oceans) which cannot simulate stratification processes. Models in this category include CBCM (Walton et al. 1983) and the models of Leendertse et al. (1973) which simulate hydrodynamics and the transport of salt, temperature, and other conservative constituents.

Sample Applications of Estuary Models

Delineation of Aquatic Use Segments. Figure II-7 illustrates the use of measured data on physical parameters to delineate homogeneous aquatic use segments in Chesapeake Bay. For many estuaries, the measured data on circulation and salinity will not have sufficient spatial and temporal coverage to permit a comprehensive analysis of use attainability zones. In cases where the measured data base is inadequate, computer models can be used to expand the physical parameter data bases for segmentation of the estuary.

Figure II-13 illustrates the use of model projections for Tampa Bay, located on the Gulf Coast of central Florida, to delineate relatively homogeneous segments for use attainability evaluations (Camp Dresser & McKee, Inc. 1983). Tampa Bay is considerably smaller and shallower than Chesapeake Bay, with a surface area (approx. 350 sq. mi.) that is less than 10 percent of the Maryland/Virginia estuary's (approx. 5,000 sq. mi.

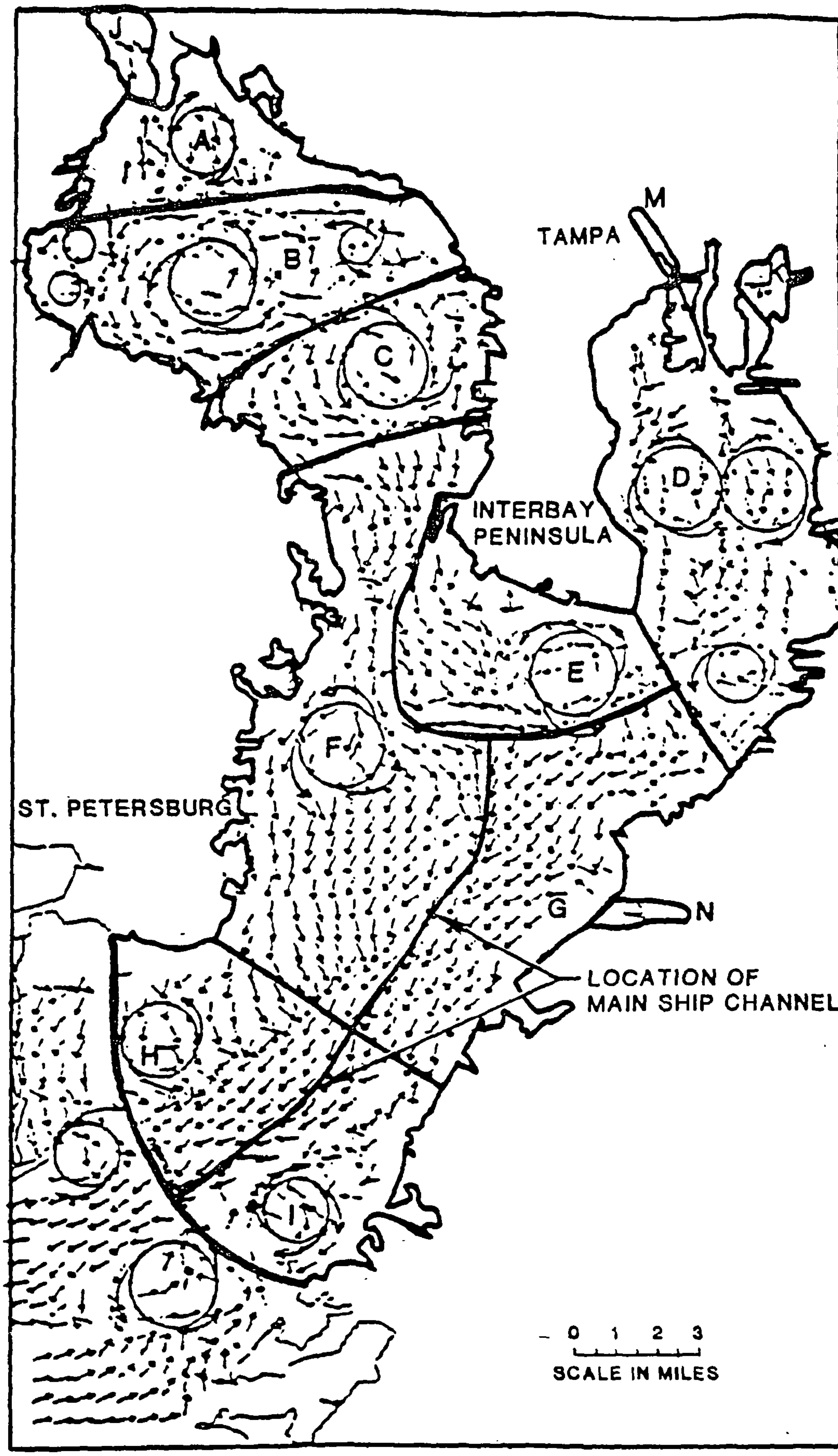


Figure II-13. Map of Tampa Bay Showing Sample Estuary Segments (A through N) and Net Current Velocities for a Single Tidal Cycle (from Camp Dresser and McKee 1983) including tributaries). The Tampa Bay estuary exhibits extremely diverse and abundant marine life which has been attributed to the geographic position of the estuary between temperate and subtropical waters. As a result of Tampa Bay's location, winter water temperatures rarely fall to levels which could kill tropical organisms and summer water temperatures are moderate enough to be tolerated by many of the temperate species. Another contributing factor to the diversity and abundance of Tampa Bay marine life is that salinity is typically in the range 25-35 ppt over most of the estuary, without the wide fluctuations and significant vertical stratification that characterize many other estuaries. As a result of the stability of the salinity regime, many ocean species can coexist with typical estuarine species.

Tampa Bay's salinity regime is also much different from Chesapeake Bay's. Whereas extensive areas in Chesapeake Bay exhibit vertical stratification, Tampa Bay is very well-mixed vertically due in large part to its relatively shallow mean depth (i.e., relationship of storage volume to surface area). Unlike Chesapeake Bay where circulation and mass transport must be evaluated in the vertical as well as horizontal and longitudinal directions, only the horizontal and longitudinal directions need to be considered for Tampa Bay evaluations. Therefore, the sample analysis of Tampa Bay is a good example of a segmentation approach to an estuary where the use is not significantly influenced by vertical stratification. It is also a good example of how an estuary circulation model can be used to segment an estuary for use attainability analyses.

The estuary segment boundaries shown in Figure II-13 have been delineated on a map of Tampa Bay showing circulation model projections of net current velocities (i.e., magnitude and direction) for a single tidal cycle. The model projections are based upon a two-dimensional circulation model (horizontal and longitudinal directions) which had previously been calibrated to measured current velocity and tidal elevation data for Tampa Bay (Ross and Jerkins, 1978). The use of the model expanded the available circulation data base from a limited number of gaging stations to comprehensive coverage of the entire Bay. One of the most important factors in subdividing the Tampa Bay estuary system into relatively homogeneous subunits is the ship navigation channel extending from the mouth of the Bay to the vicinity of Interbay Peninsula with branches extending into Hillsborough Bay (segment D) and into the lower end of Old Tampa Bay (segment C). As may be seen from the convergence of velocity vectors in the vicinity of the navigation channel, there tends to be relatively little mixing between waters on either side of the Main Bay channel. Therefore in Figure II-13, the navigation channel and the adjoining dredge spoil areas serve as the approximate boundary between segments H and I and between segments F and G. Each of these segments appears to be relatively isolated from its counterpart on the opposite side of the navigation trench before mixing occurs in the vicinity of the navigation channel, thereby justifying the designation of each as a separate segment. Water movement is also somewhat isolated on approximately either side of the navigation channel branches extending into Hillsborough Bay and the lower end of Old Tampa Bay. However, since net current velocities tend to converge a short distance south of the two ship channel branches, the boundaries between segments E and F and E and G in Figure II-13 depart somewhat from the navigation trench.

Another circulation factor considered in the delineation of estuary segments is the impact of causeways and bridges on tidal flushing. Based upon the circulation patterns shown in Figure II-13, it seems appropriate to assign separate segment designations (A, B, and C) to the areas above the three bridge crossings in Old Tampa Bay: Courtney Campbell Causeway (boundary between segments A and B), Howard Franklin Bridge (boundary between segments B and C) and Gandy Bridge (boundary between segments C and F). Likewise, McKay Bay (segment K), which is separated from Hillsborough Bay by the 22nd Street Causeway, also merits a separate segment designation.

A final circulation factor in the open bay is the location of net rotary currents (indicated by circles in Figure II-13) which are called "gyres." The gyres result from water moving back and forth with the tides, while following a net circular path. Gyres can have a significant effect on flushing times, since waters caught in the gyres typically exhibit much higher residence times than waters which are not affected by these areas of net rotary currents. The use of the main ship channel and causeway/bridge crossings as segment boundaries in Figure II-13 has generally isolated the major gyres or groups of gyres. Further subdivision of the Hillsborough Bay segment (D) to isolate the waters on the eastern and western sides of the ship channel (which bisects segment D) does not appear to be warranted because of the two gyres in the middle section of the Bay and the gyre in lower Bay. In other words, the gyres in Hillsborough Bay are indicative of an irregular circulation pattern that seems to mix waters on both sides of the ship channel. Likewise, the gyres within segment B are indicative of a circular mixing pattern throughout the segment which suggests that further subdivision into eastern and western sections is not justified.

The segment network in Figure II-13 also maintains relatively homogeneous salinity levels within each segment. The greatest longitudinal variations in salinity occur in segments F and G which exhibit 3-5 ppt increases in average annual values between the upper and lower ends of the segment. If these longitudinal variations in salinity will result in significant differences in the biological community, further subdivision of segments F and G should be considered.

Figure II-13 also shows five separate segments for significant embayments: Safety Harbor (J), McKay Bay (K), Alafia River (L), Hillsborough River (M), and Little Manatee River (N). The latter three represent the tidal sections of the indicated river. In addition to these five embayments there may be other inlets which should be separated from Tampa Bay segments for separate use attainability studies.

In summary, the network shown in Figure II-13 illustrates how hydrodynamic and salinity data produced by an estuary model can be used to segment the Tampa Bay system. In addition to the type of hydrodynamic data shown in Figure II-13, the estuary model can be used for "particle tracer" studies that can further address issues such as mixing of waters on either side of the ship channel and the impacts of gyres.

Evaluation of Use Attainment Based Upon Ambient Water Quality Data. It is often the case that the measured ambient water quality data base is inadequate from temporal and/or spatial standpoints for a definitive assessment of use attainment.

An example of temporal limitations is an ambient water quality data base that suffers from a small sample size (e.g., 6-12 slackwater observations at each station per year), thereby resulting in extremely wide confidence intervals for the number of violations of standards and criteria that are attributable to random variations (rather than actual water quality deterioration).

Another example of temporal limitations is an observed water quality data base that is restricted to a single daytime observation on each sampling day. This type of data base may not provide any insights into diurnal variations in DO which can result in use impairment, since nighttime DO's can be significantly lower than daytime values due to diurnal variations in algal production/respiration.

An example of spatial limitations in the measured water quality data base is inadequate coverage of longitudinal and/or horizontal variations in water quality. Adequate longitudinal coverage is required in all estuaries to assess the significance and spatial extent of maximum and minimum concentrations in the estuary. Adequate horizontal coverage is required in relatively wide estuaries where horizontal transport processes are significant.

Another example of spatial limitations would be the collection of surface water samples only within an estuary which exhibits extensive areas of vertical stratification. The lack of bottom water samples may prevent an adequate assessment of use attainment, since potential depressions of bottom water DO levels cannot be evaluated.

In cases where the measured water quality data base is inadequate from either temporal or spatial standpoints, an estuary model should be used to expand the data base for use attainability evaluations. The model must first be calibrated with the available measured data base to demonstrate that its representation of the prototype produces water quality statistics that are not significantly different from the measured statistics. The reliability of the estuary model projections depends upon the amount and type of measured data available for model calibration. If the measured data base provides reasonably good coverage of spatial and temporal (e.g., both short-term and long-term) variations in water quality, projections by a model calibrated to this data base should be quite reliable in a statistical sense. If the measured data base used for calibration is quite limited, estuary model projections will be less reliable; however, the application of an appropriate model to an estuary with limited measured data can still provide significant insights for use attainability evaluations and considerable guidance for future estuary monitoring programs.

To illustrate the use of an estuary model for use attainment evaluations, a sample application of a one-dimensional (1-D) model to Naples Bay, Florida is described below (Camp Dresser & McKee, Inc. 1983). Naples Bay (see Figure II-14) is a rather small estuary (less than 1.5 sq. mi. surface

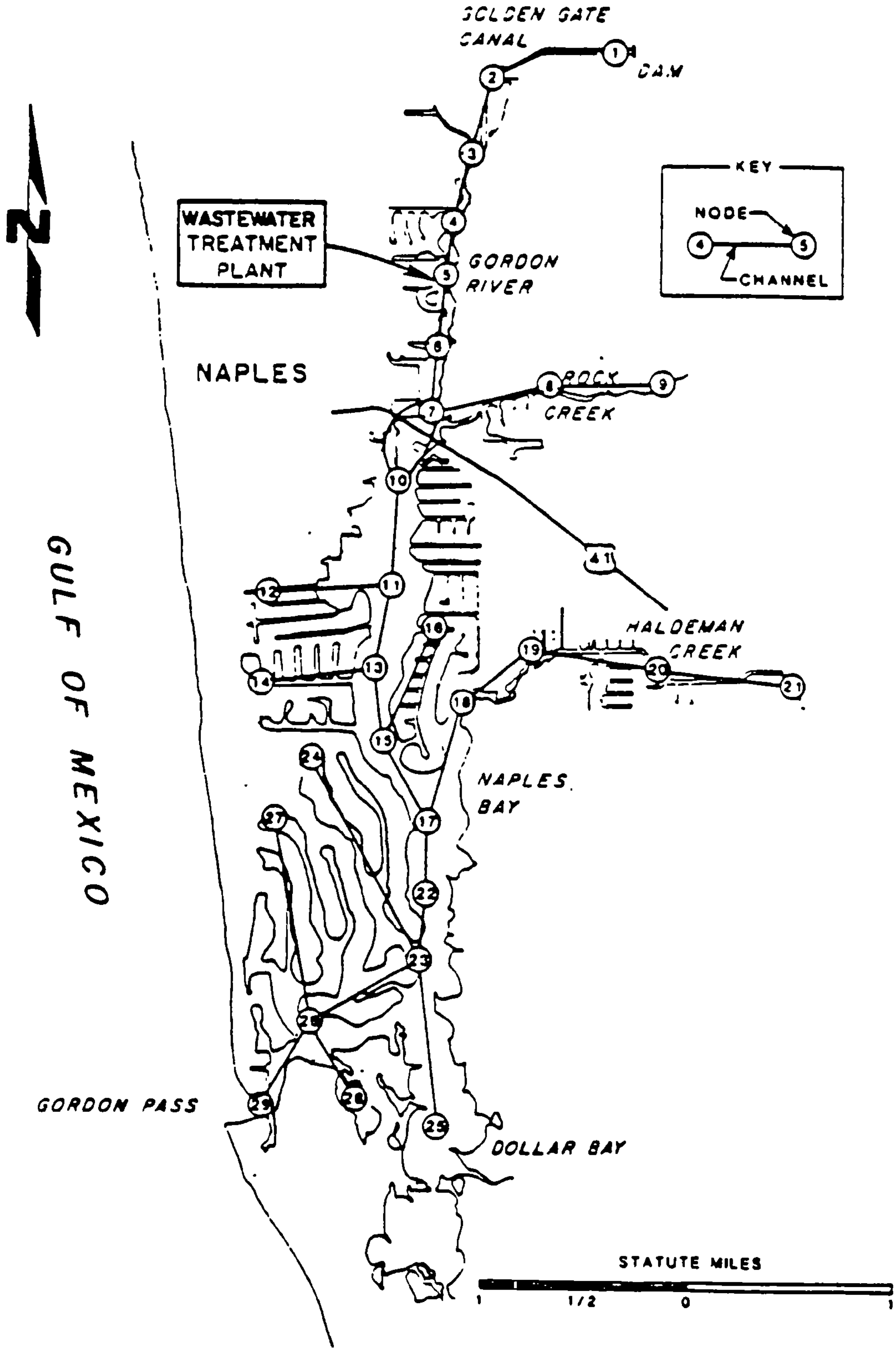


Figure II-14. Node and Channel Network for the Naples Bay DEM model.

area) located on the Gulf Coast of southeastern Florida. The City of Naples' municipal wastewater treatment plant (secondary treatment) which discharges to the Gordon River portion of the Naples Bay estuary, is the only major point source of pollution. This sample application illustrates the impacts of an 8.0 million gallons per day (mgd) discharge from the Naples wastewater treatment plant. Nonpoint pollution loadings are contributed by rainfall runoff and groundwater recharge from a 155 sq. mi. drainage area, the majority of which discharges to the estuary at the uppermost point in the system (node no. 1 in Figure II-14). The Gulf of Mexico boundary condition (introduced at node no. 29 in Figure II-14) also contributes nutrients and other constituents to the lower Bay. Since the Naples Bay system is a relatively narrow and shallow estuary, it was assumed that a 1-D model which only represents longitudinal transport would be adequate for this water quality evaluation (i.e., horizontal and vertical gradients are neglected). A schematic of the 1-D representation of the Naples Bay system with the Dynamic Estuary Model (DEM) is shown in Figure II-14.

As indicated in the earlier section on modeling techniques, the DEM model (Genet et al., 1974) applied to Naples Bay is one of the most widely used estuary models in the U.S. DEM provides a representation of intertidal hydrodynamics and mass transport with computation intervals which are typically less than one hour. The model simulates 1-D flow, mass transport, and water quality processes in a network of channels connected by junctions called "nodes." As shown in Figure II-14, the DEM model network applied to Naples Bay consists of 29 nodes and 28 channels. This network includes all the appropriate conveyance and storage features of the prototype system, including bifurcation around an island (between nodes 7 and 10), and the canal system adjacent to the main water body. Streamflows, wastewater discharges, and associated pollutant loadings are added to the system at the nodes. Based upon a set of motion equations solved for the channels and a set of continuity equations solved for the nodes, the hydrodynamic portion of the model calculates flows and velocities in the channels and water surface elevations at the nodes. An accurate representation of hydrodynamic processes within the system is developed to adequately model mass transport and water quality processes.

The output from the hydrodynamic model becomes input to the water quality model which calculates mass transport between nodes and calculates changes in concentration due to physical, chemical and biological processes. Water quality processes represented by this portion of the model include: mass transport based upon advection and dispersion, BOD decay, nitrification, algal productivity, benthic sources of pollutants, dissolved oxygen sources and sinks, and fecal coliform die-off.

Following calibration and verification of the Naples Bay model with measured hydrodynamic and water quality data, the model was used to assess estuary-wide water quality. Figure II-15 shows the model projections of wet season chlorophyll-a (i.e., phytoplankton concentrations) for secondary treatment operations which were in effect at the Naples wastewater treatment plant. As indicated in an earlier section, chlorophyll-a is an important indicator of estuary health for use attainability evaluations.

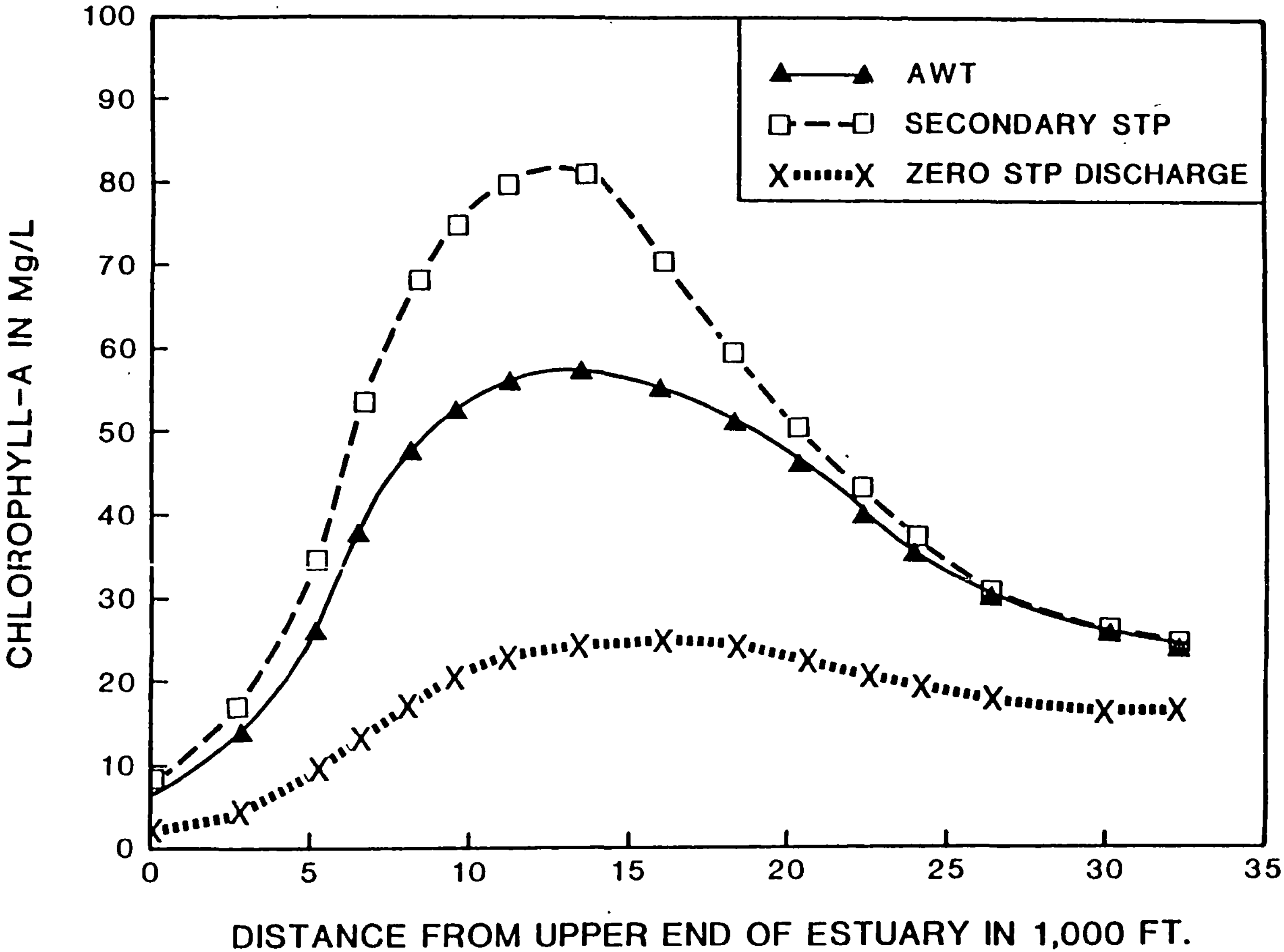


Figure II-15 Comparison of Simulated Average Daily Chlorophyll-a in Main Stem of Naples Bay Projected for Different Wastewater Discharge Scenarios: "Worst Case" Wet Season Conditions

The chlorophyll-a simulations shown in Figure II-15 represent "worst case" water quality conditions at the start of the wet season (i.e., 4-month period of significant rainfall and high streamflow). As may be seen from the plot of "Secondary STP" conditions along the main stem of the Bay, the combination of point and nonpoint source loadings of nitrogen and phosphorus under wet season conditions results in chlorophyll-a levels exceeding 50 ug/l for almost 3.0 miles and maximum values on the order of 80 ug/l for about 1.0 mile. The volume-weighted mean chlorophyll-a (i.e., weighted by the storage volume in each estuary segment) for the upper two miles (i.e., Gordon River) of the estuary is about 60 ug/l, while the volume-weighted mean for the entire estuary is about 45 ug/l. These maximum and mean concentrations can be compared with state or regional water quality criteria for local use attainability evaluations. Additional model projections can be developed for other wet season and dry season conditions to evaluate the frequency of use impairment expressed in terms of ambient water quality. Since chlorophyll-a impacts are primarily of interest in terms of associated impacts on DO, the estuary model can also be used to evaluate diurnal DO impacts for use attainability assessments. Once chlorophyll-a and DO relationships have been evaluated, the estuary model can be used to evaluate nitrogen and phosphorus goals that maintain chlorophyll-a at levels ensuring use attainment.

Evaluations of Use Impairment Causes and Alternative Controls. Estuary models are probably most useful for management evaluations following a determination of use impairment in certain sections of the estuary. Models can be used to define the causes of impairment and to define the effect of alternate controls on attaining the use. Such analyses require the development of causal relationships between pollution loadings, physical modifications and the resulting changes in uses. It is very difficult to develop such causal relationships from statistical analyses of measured data. For example, regression equations can merely indicate that pollution loadings and impairment of the uses appear to be correlated based upon the measured data base. Such regression equations should not be interpreted as definitive indications of cause-effect relationships. Evaluations of cause-effect relationships require the use of a deterministic estuary model.

Evaluations of use impairment causes will typically focus on comparisons of point and nonpoint source pollution impacts. The estuary model is well-equipped to perform such evaluations because both point and nonpoint source loadings can be "shut off" (i.e., deleted from the system) for evaluations of relative contributions to use impairment. Applications of the Naples Bay model will be used to illustrate how evaluations of cause-effect relationships can be performed. After analyses of the impacts of existing secondary treatment operations at the 8.0 mgd wastewater treatment plant, the Naples Bay model was rerun with no wastewater discharges. For this model run, the only sources of nutrients and other constituents were nonpoint source flows from the Bay's 155 sq. mi. drainage area and ocean boundary conditions at the mouth of the Bay. The resulting chlorophyll-a projection for "worst case" wet season conditions are shown in Figure II-15 as the "Zero STP Discharge" plot. As may be seen, the maximum chlorophyll-a concentration is about 25 ug/l, with concentrations on the order of 15-25 ug/l for about 5.0 miles. The chlorophyll-a concentrations for the "Zero STP Discharge" condition are typically only 25-50 percent of the existing

"Secondary STP" levels for about 5.0 miles. Also, the location of the maximum chlorophyll-a concentration is shifted about 1.0 mile further downstream for the "Zero STP Discharge" condition. The mean volume-weighted chlorophyll-a for the entire Bay is approximately 20 ug/l which is less than half of the "Secondary STP" mean. These evaluations suggest that secondary effluent discharges from the wastewater treatment plant are the major cause of relatively high chlorophyll-a levels under wet season conditions. Approximately 50-55 ug/l or about 70 percent of the peak chlorophyll-a concentration (80 ug/l) and about 25 ug/l or 55 percent of systemwide volume-weighted mean concentration can be attributed to the wastewater treatment plant.

Chlorophyll-a is a specific index of phytoplankton biomass. Thus, assuming that the chlorophyll-a levels associated with the "Secondary STP" condition indicate use impairment, the estuary model provides a mechanism for evaluating the use attainability benefits of alternate controls. The Naples Bay model was rerun with the 8.0 mgd discharge upgraded to advanced wastewater treatment (AWT) levels. The simulated AWT upgrading involved reducing total phosphorus effluent levels from 7.0 mg/l to 0.5 mg/l as P, the achievement of almost total nitrification in comparison with less than 50 percent nitrification for secondary treatment conditions, and reducing 5-day biochemical oxygen demand (BOD) from 20 mg/l to 5 mg/l. Nonpoint source loadings and ocean boundary conditions were set at the same levels as the "Secondary STP" model runs. As shown in Figure II-15, the projected chlorophyll-a concentrations for the "AWT" conditions are 20-30 percent lower than the "Secondary STP" levels for approximately a two mile section that includes the maximum concentrations for both scenarios. The AWT scenario's maximum concentrations of chlorophyll-a are on the order of 50-60 ug/l for about 2.5 miles, while the volume-weighted mean concentration for the entire Bay system is about 40 ug/l. Even under AWT conditions, the maximum chlorophyll-a levels for AWT conditions are still about 35 ug/l greater than the maximum values for "Zero STP Discharge" conditions.

The maximum and mean concentrations for AWT conditions can be compared with water quality criteria to determine if this control measure can achieve use attainment. If the projected chlorophyll-a reductions are not sufficient to prevent use impairment, the model can be rerun to assess the use attainability benefits of nonpoint source controls in addition to AWT implementation.

ESTUARY SUBSTRATE COMPOSITION

The bottom of most estuaries is a mix of sand, silt and mud that has been transported and deposited by ocean currents or by freshwater sources. Rocky areas may also be seen, particularly in the fjord-type estuary. None of these substrate types are particularly hospitable to aquatic plants and animals, which accounts in part for the paucity of species seen in an estuary.

Much of the estuarine substrate is in flux. The steady addition of new bottom material, transported by currents, may smother existing communities and hinder the establishment of new plants and animals. Currents may cause a constant shifting of bottom sediment, further hindering the colonization of species. Severe storms or flooding may also disrupt the bottom.

The sediment load introduced at the head of the estuary will be determined by the types of terrain through which the river passes, and upon land use practices which may encourage runoff and erosion. It is important to take land use practices into consideration when examining the attainable uses of the estuary. The heavier particles carried by a river will settle out first when water velocity decreases at the head of the estuary. Smaller particles do not readily settle and may be carried a considerable distance into the estuary before they settle to the bottom. The fines may never settle and will contribute to the overall turbidity which is characteristic of estuaries.

It is often difficult for plants to colonize estuaries because they may be hindered by a lack of suitable anchorage points, and by the turbidity of the water which restricts light penetration (McLusky, 1971). Attached plant communities (macrophytes) develop in sheltered areas where silt and mud accumulate. Plants which become established in these areas help to slow prevailing currents, leading to further deposition of silt (Mann). The growth of plants often keeps pace with rising sediment levels so that over a long period of time substantial deposits of sediment and plant material may be seen.

Attached plant communities, also known as submerged aquatic vegetation (SAV), serve very important roles as habitat and as food source for much of the biota of the estuary. Major estuary studies, including an intensive years-long study of the Chesapeake Bay, have shown that the health of SAV communities serves as an important indicator of estuary health. Although excess siltation may have some adverse effects on SAV, as discussed above, this problem is minor compared to the effects of nutrient and toxics loadings to the estuary. When SAV communities are adversely affected by nutrients and/or toxics, the aquatic life uses of the estuary also will be affected. The ecological role of SAV in the estuary will be discussed further in Chapter III, and its importance to the study of attainable uses in Chapter IV.

Sediment/substrate properties are important because such properties: (1) determine the extent to which toxic compounds in sediments are available to the biota; and (2) determine what types of plants and animals may become established. The presence of a suitable substrate may not be sufficient, however, since nutrient, DO, and/or toxics problems may cause the demise and prevent the reestablishment of desirable plants and animals. Therefore, characterization of the substrate is important to a use attainability study in order to understand what types of aquatic life should be expected in a given area.

ADJACENT WETLANDS

Tidal and freshwater wetlands adjacent to the estuary can serve as a buffer to protect the estuary from external phenomena. This function may be particularly important during wet weather periods when relatively high streamflows discharge high loads of sediment and pollutants to the estuary.

The volume of sediment carried by streamflow during wet weather periods is substantially greater than the amount transported into the estuary by rivers and streams during dry weather periods. Such shock loads could quickly smother plant and animal communities and jeopardize their survival. Wetlands can serve an important function by protecting the estuary from such shock loads. Because of the sinuous pattern of streams that flow through the wetlands, and the high density of plants, water velocities will be reduced enough to allow settlement of a substantial proportion of the sediment load before it reaches the estuary. This simultaneously protects the estuary and contributes to the maintenance of the wetlands.

The sediment load discharged by streamflow may be accompanied by nutrients and other pollutants. Excessive loadings of nutrients such as nitrogen and phosphorus may promote eutrophication and the growth of algal mats in the estuary, which is undesirable from both aquatic use and aesthetic standpoints. On the other hand, these nutrients are beneficial to the maintenance of plant life in the wetland.

Another important function of a wetland is to reduce peak streamflow discharges into the estuary during wet weather periods. To the extent that this peak flow attenuation prevents abrupt changes in salinity, the flora and fauna of the estuary are protected. It has been common practice to straighten existing channels and cut new channels in wetlands to speed drainage and enable the use of wetlands for agriculture or other development. Such channelization may diminish the protective functions of the wetland and have an adverse impact on the health of the estuary.

While the wetland may help to withhold nutrients in the form of nitrogen and phosphorus from the estuary, it serves as a major source of nutrients in the form of detritus. A substantial portion of dead plant material in the wetland is transported to the estuary as detritus. Detritus is a basic fuel of the estuary, serving as the main source of nutrient for filter feeders and many fish at the bottom of the food chain. The estuary is highly productive, more so than the freshwater or marine environment, because of this source of nutrients.

Since the alteration or destruction of wetlands may hold important implications for the health of the estuary, it is important during the course of a water body survey to examine historical trends in the wetland acreage, locations, and characteristics for clues which explain changes in the estuary and its uses. The extent to which wetlands have been irreversibly altered may establish bounds on the uses that might be expected. Conversely, restoration of wetlands may provide some means of restoring uses provided that other conditions such as toxic or nutrient loadings are not a problem, or some other irreversible change has not been made to the estuary.

HYDROLOGY AND HYDRAULICS

There are two important sources of freshwater to the estuary-streamflow and direct precipitation. In general, streamflow represents the greatest contribution to the estuary and direct precipitation the smallest.

The location of the salinity gradient in the river controlled estuary is to a large extent an artifact of streamflow. The location of salinity iso-concentration lines may change considerably, depending upon whether streamflow is high or low. This in turn may affect the biology of the estuary, resulting in population shifts as biological species adjust to changes in salinity.

Most species are able to survive within a range of salinity levels, and therefore most aquatic uses may not be adversely affected by minor shifts in the salinity gradient. Most of the biota can also sustain temporary extreme changes in salinity, either by flight or through some other mechanism. For example, molluscs may be able to withstand temporary excursions beyond their preferred salinity range by simply closing themselves off from their environment. This is important to their survival since the adult is unable to relocate in response to salinity changes. However, molluscs cannot survive this way indefinitely.

Generally speaking, the response of a stream or estuary to rainfall events depends upon the intensity of rainfall, the drainage area affected by the rainfall and the size of the estuary. Movement of the salt front is dependent upon tidal influences and freshwater flow to the estuary. Variations in salinity generally follow seasonal patterns such that the salt front will occur further down-estuary during a rainy season than during a dry season. The salinity profile may also vary from day to day reflecting the effect of individual rainfall events, but may also undergo major changes due to extreme meteorological events.

The location of the salt front in a small estuary may be easily displaced but rapidly restored in response to a rainstorm, whereas the effect of the same size storm on salinity distribution within a larger estuary may be minor. For a large system, the contribution of a given storm may be only a fraction of the overall freshwater flow and thus will have no appreciable effect. For a small system the contribution of a given storm may be very large compared to overall flow, and the system will respond accordingly.

A rapid increase in flow may have several deleterious effects on a small estuary: (1) the salinity gradient changes drastically, placing severe stress on non-motile species and forcing the migration of motile forms, (2) a sediment and pollutant load which is too large to be captured by surrounding wetlands may be transported into the estuary, and (3) the bottom may be scoured in areas of high flow velocity, destroying floral and faunal communities and existing habitat, and eliminating the conditions that would be required for replacement communities to become established.

Major shifts in salinity due to extreme changes in freshwater flow are not uncommon. An excellent example is the impact of Hurricane Agnes on the Chesapeake Bay in 1972. The enormous and prolonged increase in freshwater flow to the Bay shifted the salinity gradient many miles seaward and had a devasting effect on the shellfish population. The flow was so great that salinity levels did not return to normal for several months, a period far longer than non-motile species would be able to survive such radical reductions in salinity. In addition, the enormous quantities of sediment delivered to the Bay by Hurricane Agnes exerted considerable stress on the Bay environment.

Anthropogenic activity may also have a significant effect on salinity in an estuary. When feeder streams are used as sources of public water supply and the withdrawals are not returned, freshwater flow to the estuary will be reduced, and the salt wedge found further up the estuary. If the water is returned, usually in the form of wastewater effluent, the salinity gradient of the estuary may not be affected although other problems might occur which are attributable to nutrients and other pollutants in the wastewater.

Even when there is no appreciable change in annual freshwater flow or quality due to water supply uses, the salinity profile may still be affected by the way in which dams along the river are operated. Flood control dams may result in controlled discharges to the estuary rather than relatively short but massive discharge during high flow periods. A dam which is operated so as to impound water for adequate public water supply during low-flow periods may severely alter the pattern of freshwater flow to the estuary. Although annual input to the estuary may remain unchanged, seasonal changes may have a significant impact on the estuary and its biota.

The discussion of hydrology, meteorology and the effect of hydraulic structures in this section provides only an overview of their possible effects on the health of an estuary. Hydrologic impacts will depend upon the unique physical characteristics of the estuary and its feeder streams, including structural activity that may have changed flow characteristics to the estuary. Extreme rainfall events are particularly important because they may result in physical damage to wetlands and to the estuarine substrate, and may subject the biota to abnormally low salinities as the salt wedge is driven seaward. Extreme periods of drought may also have an adverse impact on the estuary. The operation of hydraulic structures -- dams and diversions -- can significantly alter the characteristics and the uses of an estuary. Clearly, these characteristics must be taken into account in determining the attainable uses of the water body.

CHAPTER III

CHARACTERISTICS OF PLANT AND ANIMAL COMMUNITIES

INTRODUCTION

Salinity, light penetration and substrate composition are the most critical factors to the distribution and survival of plant and animal communities in an estuary. This Chapter begins with an overview of the physical phenomena and biological adaptations which influence the colonization of the estuary. Following this, specific information is presented on Estuarine Plankton (phytoplankton and zooplankton), Estuarine Benthos (infaunal forms, crustaceans and molluscs), Submerged Aquatic Vegetation, and Estuarine Fish. There is also a short discussion of measures of biological health and diversity. This last subject is presented in much greater detail in the Technical Support Manual (U.S. EPA, November 1983).

The information in this Chapter (and its associated Appendices) has been compiled to provide an overview of the types of habitat, ranges of salinity, and life cycle and other requirements of plants and animals one might expect to find in an estuary, as well as analyses that might be performed to characterize the biota of the system.

With this information having been presented as a base, discussion in Chapter IV will be directed towards how the biological, chemical and physical data descriptive of the estuary may be synthesized into an assessment of the present and potential uses of the estuary.

COLONIZATION AND PHYSIOLOGICAL ADAPTATIONS

The estuarine environment is characterized by variations in circulation, salinity, temperature and dissolved oxygen supply. Due to differences in density, the water is generally fresher near the surface and more saline toward the bottom. Colonizing plants and animals must be able to withstand the fluctuating conditions in estuaries. Rooted plants need a stable substrate to colonize an area. Once established, the roots of aquatic vegetation help to stabilize the sediment surface, and the stems interfere with and reduce local currents so that more material may be deposited. Thus, small hummocks become larger beds as the plants extend their range.

The depth to which attached plants may become established is limited by turbidity, since they require light for photosynthesis. Estuaries are typically turbid because of large quantities of detritus and silt contributed by surrounding marshes and rivers. Algal growths may also hinder the penetration of light. If too much light is withheld from the lower depths, animals cannot rely heavily on visual cues for habitat selection, feeding, or in finding a mate.

Estuarine animals are recruited from three major sources: the sea, freshwater environments, and the land. Animals of the marine component have been most successful in colonizing estuarine systems, although the extent to which they penetrate the environment varies (Green 1968). Estuarine animals that belong to groups prevalent in freshwater habitats are presumed to have originated there. Such species comprise the freshwater component. The invasion of estuaries from the land has been accomplished mainly by arthropods.

When animals encounter stressful conditions in an estuary, they have two alternatives: they can migrate to an area where more suitable conditions exist, or if sedentary or sessile they can respond by sealing themselves inside a shell, or by retreating into a burrow.

Most stenohaline marine animals can survive in salinities as low as 10-12 ppt by allowing the internal environment (blood, cells, etc.) to become osmotically similar to the surrounding water (McLusky 1981). Such "conformers" often change their body volume. In contrast oligohaline animals actively regulate their internal salt concentration. They do so by active transport of sodium and potassium ions (Na^+, K^+). Osmoregulation relies on several possible physiological adaptations. Reduced surface permeability helps minimize osmotic flow of water and salts. In addition, the animal's excretory organs serve to conserve ions or water needed for osmoregulation.

Upper and lower tolerance limits define a range between which environmental factors are suitable for life (zone of compatibility). The adaptations of these tolerance limits are referred to as resistance adaptations. In estuaries, the major environmental factors to which organisms must adjust are periodic submersion and desiccation as well as fluctuating salinity, temperature, and dissolved oxygen.

Vernberg (1983) notes several generalizations concerning the responses of estuarine organisms to salinity: (1) those organisms living in estuaries subjected to wide salinity fluctuations can withstand a wider range of salinities than species that occur in high salinity estuaries; (2) intertidal zone animals tend to tolerate wider ranges of salinities than do subtidal and open-ocean organisms; (3) low intertidal species are less tolerant of low salinities than are high intertidal ones; and (4) more sessile animals are likely to be more tolerant of fluctuating salinities than those organisms which are highly mobile and capable of migrating during times of salinity stress. These generalizations reflect the correlation of an organism's habitat to its tolerance. Some estuarine animals are able to survive in adverse salinities, provided that the stress is fluctuating, not constant. For example, initial mortalities of the oyster drill (Urosalpinx cinerea) were very high when exposed to constant low salinity values. However, little or no mortalities occurred during ten days of exposure to low fluctuating salinities. Tolerance limits may also differ between larval and adult stages, as in the case of fiddler crabs (Uca pugilator). Adults are able to survive extended periods of 5 ppt salinity, while larvae cannot tolerate salinities below 20 ppt (Vernberg 1983). The salinity in which they were spawned may also influence larval responses.

Temperature also has an effect on salinity tolerances of organisms. Generally, cold-water species can tolerate low salinities best at low temperatures and tropical species can withstand low salinities best at high temperatures. The previous thermal history of an organism influences its resistance to temperature extremes. Acclimation to higher salinities can also broaden an organism's zone of compatibility for temperature.

The transport of oxygenated surface water to the bottom is greatly inhibited when an estuary is stratified. In addition, the solubility of oxygen in water is suppressed by salinity, so that estuarine DO levels at a given temperature may not be as high as would be seen in freshwater. As a consequence, many estuaries exhibit consistently low DO levels in the lower part of the water column, and may become anoxic at the bottom. This condition may be exacerbated by benthic DO demand. Many estuarine organisms must be tolerant of low DO. Those that are able will leave to seek areas of sufficient dissolved oxygen, while others (such as bivalves) will respond by regulating metabolic activity to levels that can be supported by the ambient DO concentration.

Intertidal organisms experience alternating periods of desiccation and submersion. These animals, mainly molluscs, are able to resist desiccation because of morphological characteristics that aid in controlling water losses. Others burrow into the moist substrate to avoid prolonged exposure to the air. Small animals with high ratios of surface area to volume are less resistant to water loss than are larger organisms.

MEASURES OF BIOLOGICAL HEALTH AND DIVERSITY

Estuaries are characterized by high productivity but low species diversity. Several authors have noted decreased species diversity in estuaries when compared to freshwater or marine systems (Green 1968, McLusky 1971, McLusky 1981, Haedrich 1983). Two major hypotheses explain the paucity of estuarine species. The first explanation is that of physiological stress caused by variable conditions in estuaries (McLusky 1981). Plants and animals must be able to withstand considerable changes in salinity, DO and temperature. In addition, because of tidal variation, they may be subjected to periods of dessication. Variable salinities are especially challenging to an organism's ability to osmoregulate. Because conditions in estuaries are not stable, fewer species inhabit estuaries than inhabit fresh or marine waters.

The second hypothesis explains decreased species diversity by the relative youth of present-day estuaries (McLusky 1971, McLusky 1981, Haedrich 1983). The estuaries that we see today probably did not exist several thousand years ago. Since this is a short period relative to the same scale over which speciation has taken place, few species have been able to adapt to and colonize the estuarine system. An investigation by Allen and Horn (1975) of several small estuarine systems in the United States revealed that a small number of species (<5) comprised more than 75 percent of the total number of individuals. Similarly, Haedrich (1983) noted that the number of fish families characteristic of estuaries comprises only six percent of the total number of families described.

Investigations of diversity in estuarine systems have employed the same diversity indices that are commonly used in freshwater systems (see U.S. EPA, 1983b, Chapter IV-2). The Shannon-Wiener index is often employed in conjunction with the two components that influence its value, a species richness index and a measure of evenness (McErlean 1973, Allen and Horn 1975, Hoff and Ibara 1977).

Because seasonal changes are so marked in estuaries, the selected diversity index should be sensitive to changes in species composition. Thus, quantitative similarity coefficients and cluster analyses may be used to determine the extent of similarity between samples. Such measures are discussed in Chapter IV-2 of the Technical Support Manual: Waterbody Surveys and Assessments for Conducting Use Attainability Analyses (U.S. EPA, 1983b).

An equal effort should be expended at each sampling station each time sampling is done. The results of a fish fauna survey may be biased by the sampling method employed. For example, the gear used (trawl, gill net, trap net, seine), the mesh size and the area in which fishing occurs determine the sizes, numbers and kinds of fish caught (McHugh 1967, McErlean 1973). Sampling gear and technique are also important in benthic and planktonic investigations. Because of the many migratory organisms found intermittently in estuaries, sampling should occur during each season of the year.

A major concern in estuarine systems is biological change due to pollution, especially alterations to commercially important populations. The ratio of annelids to mollusks and annelids to crustaceans has been used as an indication of environmental stress. By comparing these ratios to the Contamination Index (C_I) and the Toxicity Index (T_I), described in Appendix A, areas highly contaminated by metals and organic chemicals can be characterized (U.S. EPA, 1983a).

Briefly, contaminant factors (C_f) indicate the anthropogenic concentration of individual contaminants, based on metal content and Si/Al ratios in sediment. The Contamination Index (C_I) is a sum of these contaminant factors, giving equal weight to all metals, and thus has no ecological significance until combined with biotoxicity data. The map of the Chesapeake Bay in Figure III-1 illustrates the degree of metal contamination based on C_I. The Toxicity Index (T_I) is calculated using contaminant factors and EPA "acute" criteria for the metals, i.e., the concentration that may not be exceeded in a given environment at any time. This index gives information pertinent to the toxicity of sediments to aquatic life. Figure III-2 illustrates the results of calculations of Toxicity Indices for the Chesapeake Bay.

The Toxicity Index ranges from values of 1 to 20 where to lowest values denote the least polluted conditions. Characteristics associated with various values of T_I may also be seen in Chapter IV, Table IV-3. The Contamination Index is based on the calculation of the quantity C_f (see Appendix A) where $C_f=0$ when observed and predicted metal concentrations in sediment are the same, $C_f<0$ when the observed is less than the predicted, and $C_f>0$ when the observed is greater than the predicted.

The juvenile index is often used to help predict future landings of certain commercially important fish in estuaries. The juvenile index is simply the number of first year fish of a species divided by the number of seine

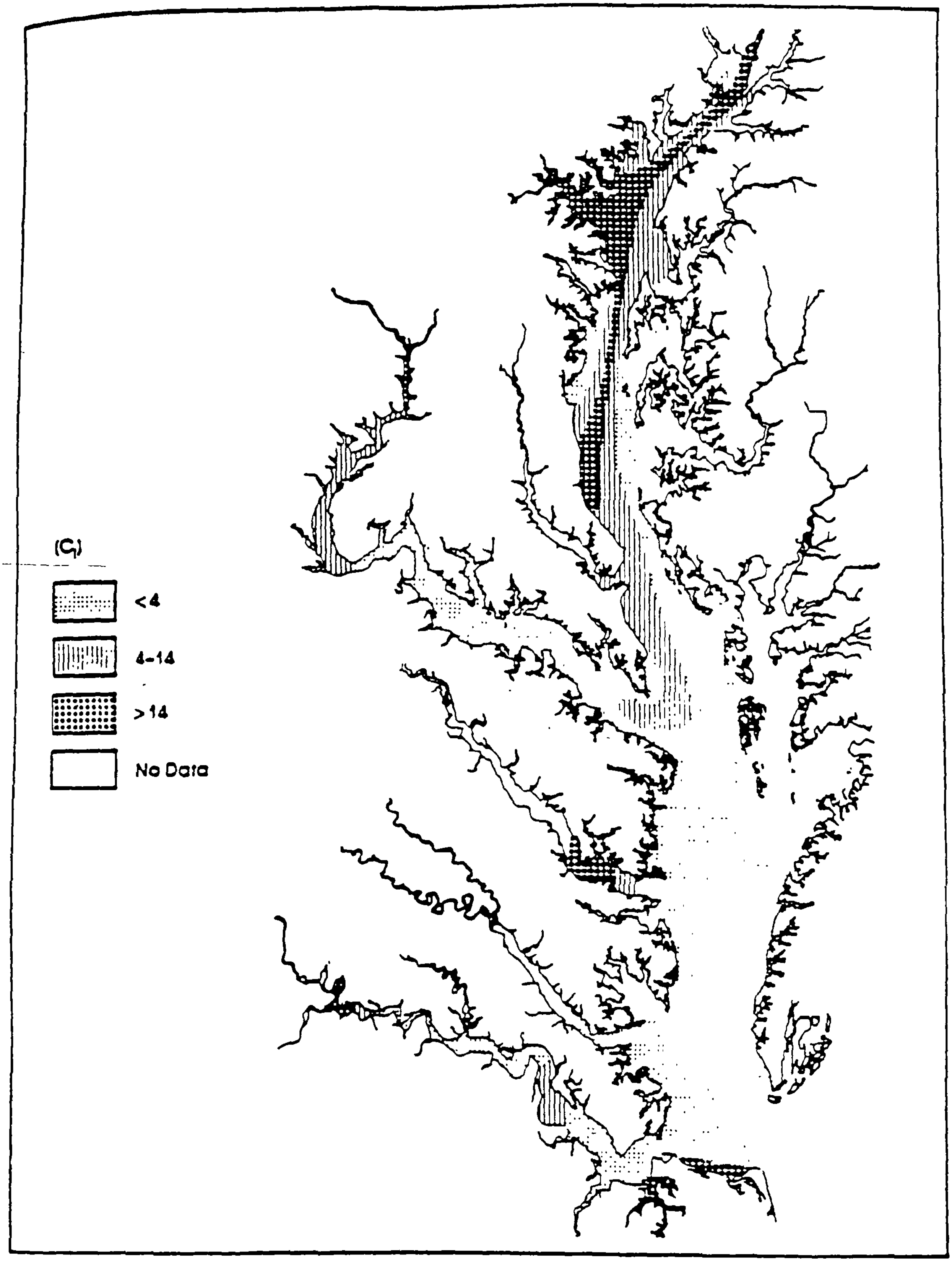


Figure III-1. Degrees of metal contamination in the Chesapeake Bay based on the Contamination Index (C_I). (from USEPA 1983c)

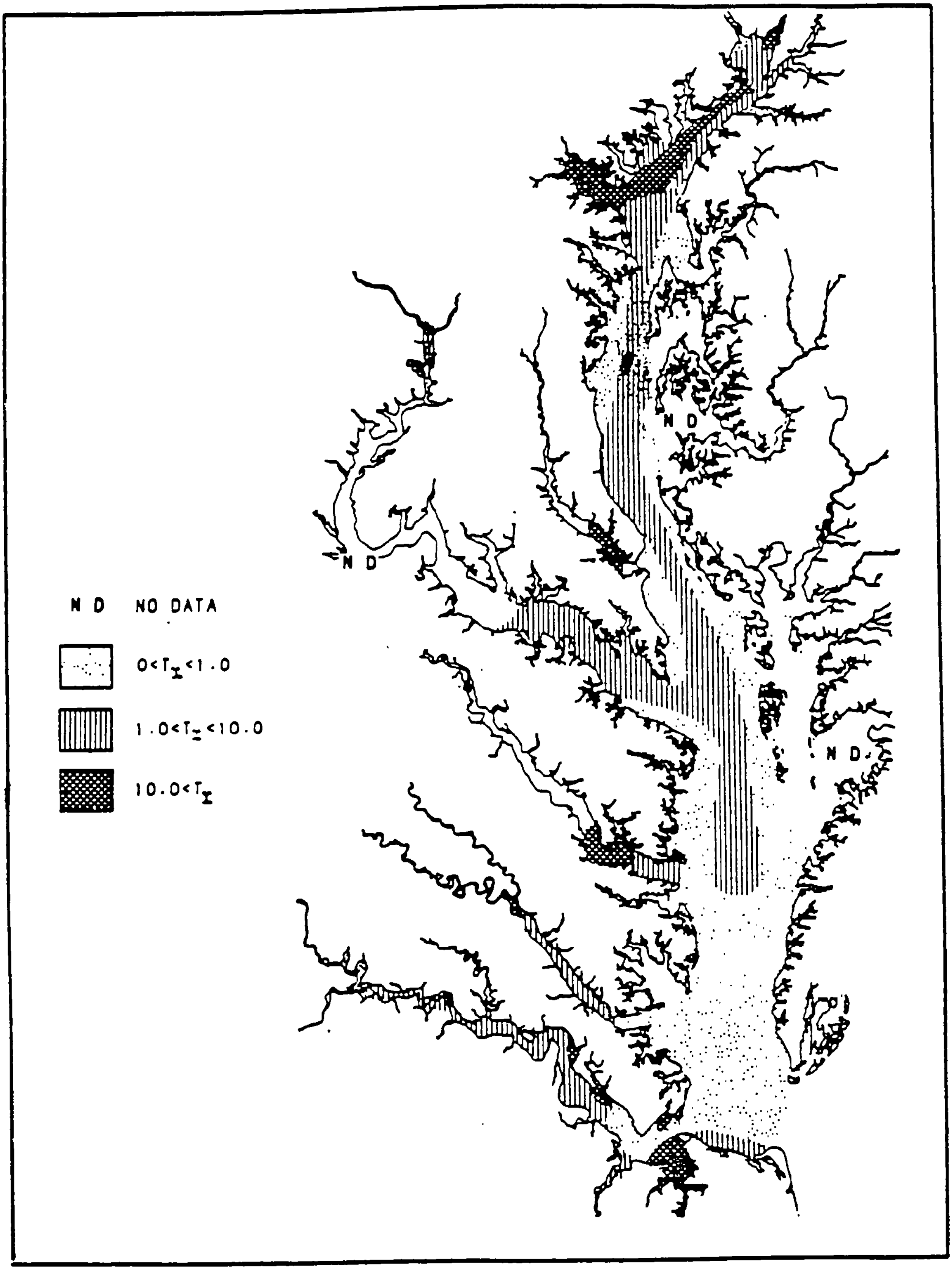


Figure III-2. Toxicity Index of surface sediments in Chesapeake Bay.
(from USEPA 1983c)

hauls. This index is then compared to juvenile indices from previous years along with commercial fisheries landings data.

In summary, species diversity in estuaries is generally lower than in adjacent freshwater or marine ecosystems. Either the changing environment or the youth of estuaries or perhaps a combination of both is responsible for this lack of species diversity. Indices of diversity that are used in estuaries are the same as those employed in freshwater studies and have been summarized in a previous document (U.S. EPA, 1983b).

ESTUARINE PLANKTON

Plankton include weak swimmers and drifting life forms. Most planktonic organisms are small in size, and although they may be capable of localized movement, their distribution is essentially governed by water movements. Because of their unique salinity conditions and currents, individual estuaries have characteristic plankton populations.

Phytoplankton

Three principal groups are included in the phytoplankton. They are diatoms, dinoflagellates and nanoplankton. Like the phytoplankton of freshwaters and oceans, estuarine phytoplankton require nutrients (such as phosphorus, nitrogen, silicon), vitamins, iron, zinc and other trace metals for growth. For photosynthesis to occur, adequate light must be available. Suitable salinities must also be present for phytoplankton populations to survive.

Nutrients generally are abundant in estuaries. Seasonal fluctuations in nitrogen and phosphorus levels are often evident, and are related to overland runoff and fertilizer application to agricultural lands. External sources are not entirely responsible for nutrient levels in estuaries. Cycling within estuaries also plays a role in plankton productivity. Thus the turnover, or replenishment time (R), of nutrients is significant in determining their availability. Replenishment time is defined as $R = [S]/Sp$, where [S] is the concentration of the nutrient in the phytoplankton and Sp is the daily production rate measured in terms of particulate content of that nutrient in the phytoplankton (Smayda 1983). Recycling mechanisms may be separated into (1) excretion of remineralized nutrients accompanying grazing by herbivorous zooplankton or benthic organisms, (2) release through sediment roiling and diffusive flux of nutrients from the interstitial water of sediments following microbial remineralization, and (3) kinetic, steady-state exchanges between nutrients present in the particulate phase (phytoplankton, bacteria, sedimentary particles) and in the dissolved phase. The importance of each of the preceding mechanisms is dependent upon characteristics, viz. depth and vertical mixing, of specific estuaries.

Although the phytoplankton of estuaries is an integral part of the ecosystem, its role is somewhat less important than in marine or freshwater lake ecosystems. This is due partly to the large quantities of detritus and bacteria that serve as an alternative food source for many primary consumers. Estimates of primary production are generally calculated from the utilization of nutrients (phosphates, C^{14} uptake, chlorophyll concentration) (Perkins 1974). The phytoplankton contribution to primary productivity is often minimal in many coastal plain estuaries. Although nutrients are abundant there, other factors limit phytoplankton production. At the compensation depth, the amount of oxygen produced by photosynthesis is equal to the amount utilized in respiration. Because of high turbidity, the compensation depth in estuaries is relatively shallow thus limiting the volume of water in which positive production occurs. Several authors maintain the importance of phytoplankton in supporting estuarine food webs, although the degree of contribution is controversial. Boynton, et al. (1982) provides a review of factors affecting phytoplankton production by comparing numerous estuarine systems.

The flushing time of an estuary also affects the phytoplankton population. Many estuaries have a relatively long flushing time and stable populations are able to develop. The Columbia River estuary has a stable system with a gradation from freshwater to brackish to marine plankton. In contrast, the Margaree River (the Gulf of St. Lawrence) is drained completely at low water and has no such gradation. Thus, high tide populations are typically marine, while a freshwater population is evident at low tide.

The species composition of an estuary may be unique. Narragansett Bay for example, is a shallow, well-mixed estuary located on the northeastern coast of the United States. Surface salinity ranges from 20.5 ppt near river mouths to 32.5 ppt at the mouth of the bay. Flushing time of the bay is estimated at thirty days (Smayda 1983). Because of tidal and wind-induced mixing, most of Narragansett Bay has neither a well-defined halocline or thermocline. Seasonal variation of plankton is evident, although the diatom Skeletonema costatum represents about 80% of total numerical abundance over the annual cycle (Smayda 1983). The major phytoplankton bloom occurs during December, coinciding with the minimum incident radiation and length of day. Blooms are regulated by temperature, light, nutrients, grazing, hydrographic disturbances and possibly species interactions. Neither blue-green algae nor dinoflagellates are important in Narragansett Bay due to its relatively high salinity. Planktonic blue-green algae tend to be more important in reduced salinities. Dinoflagellates (viz. Prorocentrum triangulatum, Peridinium trochoideum, Massartia rotundata, Olisthodiscus luteus) occur sporadically during the summer months, although diatoms continue to predominate. A succession of diatom species occurs seasonally, although Skeletonema is prevalent during all months. Detonula confervacea and Thalassiosira nordenskioeldii, important secondary species during the winter-spring bloom, are replaced by Leptocylindrus danicus, L. minimus, Cerataulina pelagica, Asterionella japonica, and Rhizosolenia fragilissima.

Phytoplankton in the Navesink River, New Jersey, were studied by Kawamura (1966). Based on salinity, several zones with characteristic phytoplankton were defined. Euglenoids dominated below 20 ppt. The zone in which salinity lay between 20 and 22 ppt was populated by Rhizosolenia. Cerataulina bergonii dominated in salinities ranging from 22 to 25 ppt. Dinoflagellates, including Peridinium conicoides, P. trochoides, and Glenodinium danicum, were prevalent in the outer region of the estuary. Open water beyond the mouth of the estuary was populated mostly by Skeletonema costatum. For regions with a fairly stable salinity gradient, Kawamura (1966) noted the dominant forms as presented in Table III-1.

TABLE III-1. DOMINANT PHYTOPLANKTON IN DEFINED SALINITY REGIONS

Salinity	Dominant Forms
2-5 ppt	Anabaenopsis sp., Microcystis sp., Synedra ulna, Melosira varians.
9-10 ppt	Anabaena flos-aquae, Melosira varians, Chaetoceros sp., Biddulphia spp., Coscinodiscus sp.
16 ppt	Euglenoids
20 ppt	Melosira varians, Chaetoceros debilis, Ditylum brightwelli, Peridinians.
24-31 ppt	Skeletonema costatum, Rhizosolenia longiseta, Biddulphia aurita, Ditylum brightwelli, Dinophyceans.

from Kawamura (1966).

Zooplankton

Zooplankton commonly found in estuarine reaches have been divided into the following groups based upon their origins and salinity tolerances: (1) Marine Coastal species, (2) Estuarine, and (3) Freshwater. One of the dominant copepods in estuaries is Acartia tonsa. Although it is not utilized directly by humans, A. tonsa is a major food source for fish or invertebrates that are consumed by humans (Jones and Stokes Assoc. 1981). Several surveys of the zooplankton in Narragansett Bay have been conducted and are summarized in Miller (1983). Copepods were the dominant group, comprising 80% or more of the individuals on an annual average. Important species were Acartia clausi, A. tonsa, Pseudocalanus minutus and Oithona spp. Rotifers were abundant in late winter, and cladocerans were abundant in early summer. Flushing reaches a peak in March-April, coinciding with a low in biomass.

Zooplankton have also been studied extensively in the Chesapeake and Delaware Bays, resulting in the following list of predominant species:

(1) Coastal:

copepods - Centropages typicus, C. hamatus, Labidocera aestiva, Temora longicornis, Paracalanus parvus, Pseudocalanus minutus;

cladocerans - Penilia avirostris, Evadne nordmanni.

(2) Estuarine:

copepods - Acartia tonsa, Acartia clausi, Eurytemora affinis, Scottolana canadensis (harpacticoid), and Pseudodiaptomus coronatus;

cladocerans - Podon polyphemoides.

(3) Freshwater:

copepods - Cyclops viridis;

cladocerans - Bosmina longirostris.

Grazing by zooplankton is an important factor in the control of phytoplankton populations, although the precise role played is not yet well-defined. The population dynamics of zooplankton on the east coast, including seasonal cycles and predation by ctenophores, is covered extensively by Miller (1983). Ctenophores have not been observed in Yaquina Bay, Oregon, and it is probable that fish predators limit zooplankton densities.

Comparatively less information is available on Gulf coast zooplankton distributions than for the Atlantic coast. Some references for zooplankton community structure and distributions in Louisiana estuaries and coastal waters are: Brice, 1983; Binford, 1975; Cuzon du Rest, 1963; Drummond, 1976; Gillespie, 1971.

Planktonic larval forms of organisms such as oysters and crabs are included in the temporary zooplankton. The veliger larvae of molluscs become part of the plankton during the spring and summer. Some estuarine worms also have planktonic larval forms. The occurrence of these forms is governed by the breeding season of the adults. Environmental tolerances of the larval forms of the blue crab (Callinectes sapidus) and the American oyster (Crassostrea virginica) are found in Appendix B (e,f).

To persist in an estuary, zooplankton, like phytoplankton, must have rates of population increase at least equal to the rates of loss due to tidal flushing and river flow. High flushing rates generally prohibit the development of an endemic plankton population, and the plankton found merely resemble those found in the ocean offshore. Studies of population budgets have been made on a few estuaries (Narragansett Bay, Great Pond, Moriches Bay) and are mentioned briefly by Miller (1983).

The following articles contain information on methods in zooplankton research: Computer and electronic processing of zooplankton (Jeffries 1980); Gear used (Schindler 1969, Josai 1970); Sampling for biomass-standing stock (Ahlstrom et al. 1969, Colebrook 1983, Tranter 1968); Fixation and preservation of zooplankton (Steedman 1976); Icthyoplankton (Smith and Richardson 1977).

ESTUARINE BENTHOS

Those organisms which live on or in the bottom of any water body are the benthos. Plants such as diatoms, macroalgae and seagrasses comprise the phytobenthos, while the zoobenthos includes the animals occupying this habitat. The estuarine zoobenthos will be discussed in this section. The zoobenthos is generally divided into macro-, meio- and microbenthos. Meiobenthos pass through a 1- or 2-mm sieve, but are larger than 100 um;

macro- and microbenthos are respectively larger and smaller than meiobenthos (Wolff 1983).

Although the diversity of the benthos in estuaries is low compared to other ecosystems, benthic production is relatively high. A high level of food (detritus and plankton) and shallow depths contribute to the characteristically high benthic production noted in estuaries. Detritus is readily available to the benthos because it sinks through the shallow water. In addition, waves and tidal currents promote resuspension of particles, making them available to filter-feeders. The predominance of relatively opportunistic species, with one or more generations per year, results in a high turnover of biomass and thus high production. Macrofauna have high biomass and low turnover times and hence have economic and commercial value. Meiofauna, with low biomass and high turnover rate, play an essential role as nutrient regenerators and food for higher trophic levels (Tenore et al. 1977, McIntyre and Murison 1973, Ajheit and Scheibel 1982).

Infaunal Forms

The benthos comprises invertebrates such as thread worms, bristle worms, ostracods, and copepods as well as commercially important species of crustaceans and molluscs. Nematodes (Nematoda, thread worms) dominate the shallow water meiofauna of estuarine sediments. In addition to nematodes, permanent meiofauna include copepods, gastrotrichs, oligochaetes, rotifers and turbellarians. Juvenile macrofauna comprise the temporary meiofauna. Generally, coarser sediments support a greater diversity of species than finer estuarine sediments (Ferris and Ferris 1979). Polychaetes (Polychaeta:Annelida, bristle worms) are abundant in the soft bottom, especially within the sediment of intertidal mud flats.

Studies have used polychaete populations to characterize water bodies as having healthy, polluted, or very polluted bottoms. The use of benthic organisms as indicator species is well-documented for freshwater studies whereas studies in the estuarine/marine environment are relatively few (Reish 1979). Although the species composition in freshwater is different than marine species composition, the concept of using benthic communities as indicators of pollution remains the same. In estuarine systems, polychaete species composition changes from zones characterized as healthy to those classified as polluted. As shown in Table III-2, there is a concurrent decrease in dissolved oxygen concentration, an increase in the organic carbon content of the soil, and a reduction in the number of organisms until all species are absent (Reish 1979). However, the validity of using polychaetes as indicator species has been questioned, since polychaetes such as Capitella capitata, an opportunistic organism whose presence has often been cited as an indication of pollution, also occur in pristine estuarine areas (Reish 1979). The following literature contributions also pertain to the use of benthos as indicators of pollution: Sediment bacteria as indicators (Erkenbrecher 1980); Meiofauna as indicators (Coull et al 1981, Raffaelli 1981, Warwick 1981); Macrofauna as indicators (Gray and Mirza 1979).

TABLE III-2. SUMMARY OF BIOLOGICAL, CHEMICAL AND PHYSICAL CHARACTERISTICS OF FIVE ECOLOGICAL AREAS OF THE LOS ANGELES-LONG BEACH HARBORS[a,b].

Characteristic	Healthy bottom, *Tharyx parvus*, *Cossura candida*, *Nereis procera*	Semihealthy bottom I, *Polydora paucibranchiata*, *Dorvillea articulata*	Semihealthy bottom II, *Cirriformia luxuriosa*	Polluted bottom, *Capitella capitata*	Very polluted bottom, no animals
Number of animal species (average)					
Polychaetes	7	5	5	1	0
Nonpolychaetes	3	2	2	2	0
Dissolved oxygen (ppm) (median)					
Surface	6.0	2.5	2.5	3.5	1.6
20 ft depth	6.0	3.2	3.2	3.5	2.2
pH (median)					
Surface	7.8	7.3	7.4	7.6	7.5
20 ft depth	7.8	7.4	7.6	7.6	7.5
Substrate	7.2	7.2	7.2	7.3	7.1
Nature of substrate (in order of importance)	Gray mud, black mud, black sulfide mud	Black sulfide mud, gray clay, sand, and mud, black mud	Black sulfide mud, gray clay, black mud	Black sulfide mud	Black sulfide mud
Organic carbon of substrate (%) (median)	2.5	2.0	2.7	2.7	3.4

[a]Data from Reish (1959)
[b]Dominant species of polychaete

(from Reish 1979)

Crustaceans

Crustaceans include microorganisms such as ostracods, copepods and isopods along with commercially important macroorganisms such as crabs, shrimp and lobsters. The crabs (Arthropoda:Crustacea:Decapoda:Brachyura) that have successfully colonized North American estuarine systems are listed in Table III-3. Brachyuran crabs have a complex ontogeny. They are released from the female as zoeae, or free swimming larvae, into meso- to euhaline waters. The zoeae undergo a series of molts before reaching the megalopa stage. The megalopa metamorphoses into the first crab stage, which becomes the adult following successive molts (Williams and Duke 1983). It has been noted that above and below the preferred temperature range, the length of time required for larval development increases. Two species of Cancer that have commerical value, C. magister (Pacific Dungeness crab) and C. irroratus (Rock crab), normally enter estuaries only in high salinity regions. Larvae of C. magister and C. irroratus prefer conditions of 25-30 ppt, 10-13°C and 23.3-32.3 ppt, 13°-21°C, respectively.

Callinectes sapidus, the blue crab, supports a major fishery in the United States. The species lives in fresh water to salinities as high as 117 ppt (large males have been recorded in salt springs over 180 miles from the sea in Marion County, Florida) and from the water's edge to 35 meter depths. Appendix B (Table 1e) contains information pertaining to the life cycle of the blue crab. Additional information on general life histories of crabs and other commercially important shellfish in Gulf Coast waters is compiled by Benson (1982). The family Portunidae is also represented by Carcinus maenas in estuaries. The green or shore crab normally inhabits waters ranging in salinity from 10-33 ppt, and depths of less than 5-6 m (Williams and Duke 1979). Other crabs commonly found in North American estuaries are listed in Table III-3. Among the xanthid crabs, only Menippe mercenaria, the stone crab, has any fishery value. The major commercial fishery for stone crabs occurs in Florida, where its flesh is considered a delicacy.

Most of the information about shrimp pertains to the commercially valuable penaeid shrimp, Penaeus duorarum (pink shrimp), Penaeus aztecus (brown shrimp) and Penaeus setiferus (white shrimp). Penaeid shrimp are dependent upon estuaries during their transformation from the postlarval stage to the juvenile stage. Adults migrate from the estuarine environment to coastal and nearshore oceanic waters (Couch 1979). The life cycle of the penaeid shrimp is illustrated in Figure III-3. The range of the brown shrimp extends from Martha's Vineyard, Massachusetts, through the Gulf of Mexico to the Yucatan Peninsula, Mexico (Turner, 1983). Brown shrimp spawn in offshore marine waters deeper than 18 m (59 ft). Movement of postlarvae into estuaries has been observed from January through June in Louisiana. A peak migration from March to April was noted for Galveston Bay, Texas. Postlarval brown shrimp prefer salinities of 10 to 20 ppt, and temperatures above 15°C. Transformation from postlarvae to juveniles occurs four to six weeks after entering the estuary. Juveniles remain in shallow estuarine areas (near the marsh-water or mangrove-water interface or in seagrass beds) that provide feeding habitat and protection from predators until they reach 60 to 70 mm (2.4 to 2.8 inches) total length (TL). They move into deeper, open water, and begin gulfward migration when they reach 90 to 110 mm (3.5 to 4.3 inches) (Turner and Brody, 1983).

TABLE III-3. TAXONOMIC POSITION AND HABITAT OF DECAPOD CRUSTACEAN SPECIES, INFRAORDER BRACHYURA, OF CONCERN IN ESTUARINE POLLUTION STUDIES.

Taxon	Habitat
Infraorder Brachyura	
Section Cancridea	
Family Cancridae	
Cancer irroratus Say, Rock crab	Temperate-polyhaline
Cancer magister Dana, Dungeness crab	
Section Brachyrhyncha	
Superfamily Portunoidea	
Family Portunidae, "Swimming" crabs	
Subfamily Portuninae	
Callinectes sapidus Rathbun, Blue crab	Temperate-tropical-euryhaline
Carcinus maenas (Linnaeus), Green or shore crab	Temperate-polyhaline
Superfamily Xanthoidea	
Family Xanthidae	
Subfamily Xanthinae, "Mud" crabs	
Cataleptodius (=*Leptodius*) *floridanus* (Gibbes)	Tropical-polyhaline
Eurypanopeus depressus (S. I. Smith)	Temperate-mesohaline
Neopanope sayi (S. I. Smith)*	Temperate-mesohaline
Panopeus herbstii A. Milne Edwards	Temperate-tropical-mesohaline
Rhithropanopeus harrisii (Gould)	Temperate-oligo-mesohaline
Subfamily Menippinae	
Menippe mercenaria (Say), Stone crab	Warm temperate-subtropical-mesopolyhaline
Family Grapsidae	
Subfamily Varuninae	
Hemigrapsus nudus (Dana), Purple shore crab*	Temperate-polyhaline
Subfamily Sesarminae	
Sesarma cinereum (Bosc), Wharf crab*	Temperate-tropical-polyhaline-semiterrestrial
Sesarma reticulatum (Say), "Marsh crab"*	Temperate-polyhaline-semiterrestrial
Superfamily Ocypodoidea	
Family Ocypodidae	
Subfamily Ocypodinae	
Uca minax (Le Conte), Red jointed fiddler	Temperate-oligo-mesohaline-semiterrestrial
Uca pugilator (Bosc), Sand fiddler	Temperate-subtropical-mesopolyhaline-semiterrestrial
Uca pugnax (Smith), Mud fiddler	Temperate-mesopolyhaline-semiterrestrial

*Species intimately associated with communities reported here and pollution studies published elsewhere.

(from Williams and Duke 1979)

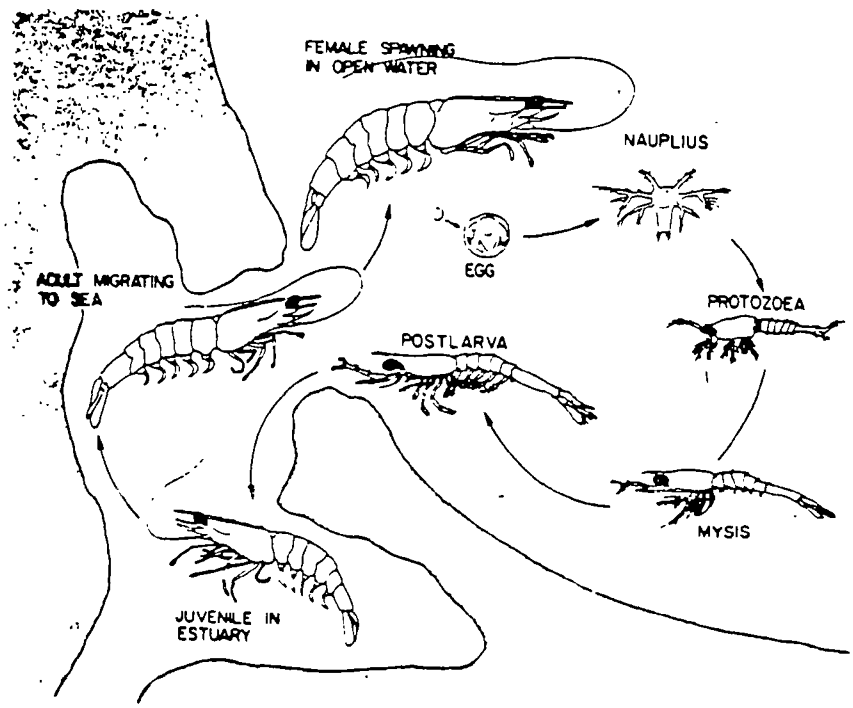


Figure III-3. Life Cycle of the Penaeid Shrimp. (from Couch 1979)

Postlarval white shrimp migrate into estuaries from late spring to early fall, and are most abundant in Louisiana estuaries from June through September. They are generally found in lower salinity waters than brown shrimp and prefer water temperatures higher than 15°C. White shrimp (120 to 140 mm) leave Gulf of Mexico embayments from September to December, as the water cools.

Finally, the grass shrimp (*Paleomonetes* sp.) of estuaries commonly live in patches of grasses growing in shallow water. Because of aquarium suitability, members of palaemonidae are often used in pollution studies.

Molluscs

The last major group in the estuarine benthos is the molluscs. The molluscs include clams, mussels, scallops, oysters and snails. Clams of major importance include *Mya arenaria* (soft shell clam), *Mercenaria mercenaria* (hard shell clam), and *Rangia cuneata* (brackish water clam).

The soft shell clam is common in bays and estuaries on both the east and west coasts of the United States, although it is commercially important only on the east coast. Soft shell clams can tolerate a wide range of salinities and temperatures. Larval development occurs at salinities from 16-32 ppt, and at temperatures of 17-23°C. Mya arenaria occurs in a variety of substrates, but prefers a mixture of sand and mud (Jones and Stokes Assoc. 1981). Hard clams (Mercenaria mercenaria) can tolerate high pollution and low oxygen levels; thus, they thrive where other species cannot compete. Hard clams prefer substrates of sand or sandy clay (Beccasio et al. 1980). The littleneck clam (Protothaca staminea) is a hardshell species found in estuaries, bays and open coastlines along the Pacific coast. It ranges from the Aleutian Islands to Socorro Island, Mexico. Minimum salinity for survival is 20.0 ppt (Rodnick and Li 1983). The brackish water clam is found in low salinity bays and estuaries from the Chesapeake Bay to Mexico (Haven 1978). Rangia cuneata can survive in fresh water, but needs brackish water for spawning (Menzel 1979).

The bay mussel (Mytilus edulis) is found worldwide in estuaries and bays. It is tolerant of variations in temperature, salinity and dissolved oxygen. Although the bay mussel is under stress at salinities less than 14-16 ppt, it can survive at 4 ppt for short periods of time. This mussel attaches to any hard substrate and may be found on rocks, stones, shingles, dead shells, ship bottoms, piers, harbor walls and compacted mud and sand (Jones and Stokes Assoc. 1981).

Bay scallops (Argopectin irradians) are usually found in shallow estuarine eelgrass beds, but may occur in depths to 18 m (Beccasio et al. 1980). They ingest detritus, bacteria and phytoplankton. The large amount of detritus consumed reflects its great availability in estuarine systems (McLusky 1981).

The American oyster (Crassostrea virginica) is a permanent resident of estuaries. It is a valuable component of east coast fisheries. Oysters prefer salinities between 14.1 ppt and 22.2 ppt, although they are able to tolerate a wider range, from 4-5 ppt to 35 ppt (Castagna and Chanley 1973). Within the range of distribution of C. virginica, the species lives in water temperatures from about 1°C (during the winter in northern states) to about 36°C (in Texas, Florida, and Louisiana) (Galtsoff 1964). Larvae develop well in depths from 2 to 8 meters at temperatures of 17.5 to 32.2°C. The oyster population in high salinities is limited by oyster drills (e.g. gastropod Urosalpinx cinerea) and parasites (MSX and Dermocystidium) (Haven 1978). Spawning by oysters is dependent upon temperature, and commences when the water reaches from 16-28°C depending upon geographic area (Bardach et al. 1972, Ingle 1951). After 6-14 days, the eggs hatch and the free-swimming larvae settle on a suitable hard substrate. Oysters filter food from the water column and deposit organic material (feces and pseudofeces) which is then available to other benthic organisms; thus, they play a valuable role in increasing the productivity of the area in which they live (McLusky 1981).

Temperature tolerances of American oysters differ with latitude. Oysters at latitudes north of Cape Hatteras can survive at temperatures less than 0°C for 4 to 6 weeks, while Gulf of Mexico oysters die if subjected to such low temperatures (Cake 1983). Temperatures required for mass spawning also differ with latitude. Apalachicola Bay reached temperatures of 26-28°C before mass spawning occurred, while a low of 16.4°C induced mass spawning in Long Island Sound, New York (Ingle 1951). Other oyster species commonly found in estuaries of the United States are Crassostrea gigas (Pacific oyster) and Ostrea edulis (flat oyster).

Snails (Gastropoda) have not been studied as extensively as the molluscs discussed above. In general, adult snails are slow moving, benthic, and able to endure a variety of temperatures and salinities. After the eggs are hatched, most snails have a planktonic stage; a few emerge as crawling juveniles. Many snails are vegetarians and scrape algae from surfaces. Some carnivorous snails use their radulas to drill holes in other shelled animals (e.g., oyster drills). Other snails consume gastropods whole, digesting the tissue and regurgitating the empty shells (Menzel 1979). More information about the distributions and habitats of NE Gulf gastropods is described in Heard (1982).

References on methodology for the study of estuarine microbiota and benthos include: Holme and McIntyre 1971, Hulings and Gray 1971, U.S. EPA 1978, Uhlig et al. 1973, de Jonge and Bouman 1977, Federle and White 1982, White et al. 1979, Montagna 1982.

In conclusion, the estuarine benthos play an important role in estuarine ecosystems. The nematodes and polychaetes, along with the commercially important shellfishes, contribute to the high productivity noted in most estuaries. The benthos are generally able to tolerate variations in temperature and salinity. Thus, they are able to live, and often thrive, in estuaries.

SUBMERGED AQUATIC VEGETATION

Submerged aquatic vegetation (SAV) plays an important role in the estuarine ecosystem, providing habitat, substrate stability and nourishment. These functions are the subject of discussion in this section. However, submerged aquatic vegetation also provides a valuable frame of reference against which to assess the health of an estuary, or portion of an estuary. The importance of SAV to an analysis of the uses of an estuarine waterbody will be discussed further in Chapter IV, Interpretation.

Role of SAV in the Estuary

Plants increase the stability of bottom sediments and reduce shoreline erosion. In addition, because the plants help to slow the tidal current, more materials may settle from suspension, augmenting the substrate and decreasing turbidity. Species differ in their ability to reduce turbidity. For example, areas dominated by Potamogeton perfoliatus (a highly branched species) were more instrumental in improving water clarity than areas where Potamogeton pectinatus (a thin-bladed single leaf species) dominated (Boynton et al. 1981).

Aquatic plants serve as both sources and sinks for nutrients. During the growing season, SAV absorbs nutrients from the water and sediments. Release of nutrients occurs when the vegetation dies. Submerged aquatic vegetation also provides valuable habitat for fish and crabs, along with molluscs and other epifauna. SAV provides shelter, spawning areas and shade for fish, while roots, stems and leaves provide firm bases for the attachment of mussels, barnacles, molluscs and other epifauna. Thus, vegetated bottoms exhibit a greater species richness than unvegetated bottoms (U.S. EPA 1982).

Stevenson and Confer (1978) cited a study (Baker 1918) which emphasized the large number of organisms associated with submerged aquatic vegetation. Over a 450 sq. mile area, Potamogeton sp. harbored 247,500 molluscs and 90,000 associated animals (total fauna, 337,500) and Myriophyllum sp. harbored 45,000 molluscs with 56,250 associated animals (total fauna, 101,250). Epiphytes and macroalgae constitute a significant and sometimes a dominant feature of SAV community production and biomass, as can be seen from Table III-4. Fish such as silversides (Menidia menidia), fourspine stickleback (Apeltes quadracus) and pipefish (Syngnathus fuscus) take advantage of this abundant epifauna for food.

Eelgrass beds also provide protection for amphipods from predatory finfish. Grass shrimp (Palaeomonetes pugio) seek protection from predatory killifish (Fundulus heteroclitus) in eelgrass beds. Young and molting crabs find shelter in areas of submerged aquatic vegetation as well.

Aquatic vegetation enters the food chain though grazing by waterfowl or as detritus passing through epifaunal and infaunal invertebrates to small and large fish. The extent to which SAV is used as a food source is determined mainly by two methods. The first is direct visual identification of material in an organism's digestive system. Such analyses are time-consuming, and the degree to which food items can be identified is often limited to larger items that are resistant to digestion. The second techique is based on $C^{12}:C^{13}$ ratios in plants and associated predators. This method assumes that animals feeding on a particular plant will, in time, reflect the food source ratio. Problems arise when animals feed on a variety of species, or if several plants have similar $C^{12}:C^{13}$ ratios. In addition, determination of $C^{12}:C^{13}$ ratios is a relatively expensive procedure.

Submerged aquatic vegetation also plays a role in nutrient cycling in estuaries. Since plants act as nutrient traps and sinks for dissolved minerals, SAV communities are capable of removing nutrients from the water column and incorporating them into biomass. Iron and calcium were found to be absorbed from the sediment by Myriophyllum spicatum. The release of nutrients and minerals occurs by excretion by living plants or by the death and decomposition of SAV.

Distribution of SAV

The distribution of SAV species is determined largely by salinity. The degree of flooding also affects vegetation distribution and is particularly important for Gulf Coast estuaries (Sasser 1977). In a study of the Chesapeake Bay, Steenis (1970, cited by Stevenson and Confer 1978) noted the following tolerance levels for Bay vegetation:

TABLE III-4. DATA FROM SELECTED SOURCES INDICATING THE PARTITIONING OF (a) PRODUCTION (Pa), $gCm^{-2}y^{-1}$ AND (b) BIOMASS gm^{-2} (ORGANIC) BETWEEN VARIOUS AUTOTROPHIC COMPONENTS OF SAV COMMUNITIES

a. Location	Species	Seagrass	Epiphytes	Benthic micro-algae	Macro-algae	Phytoplankton	Reference
Florida	Thalassia	1000	200	---	---	---	Jones 1968
Mass.	Zostera	---	20	---	---	---	Marshall 1970
Calif.	Ruppia	28	--------------	267	--------------	91	Wetzel 1964
N.Carolina	Zostera	330	73	---	---	---	Penhale 1977
Ches. Bay	Zostera[a]	0.48	0.17	-0.05	---	0.09	Murray (pers.comm.
	P.pectinatus	0.5-2.2	---	---	---	0.3-1.0	Kaumeyer et al. 19
	P.perfoliatus	1-3.0	---	---	---	0.5-1.0	Kaumeyer et al. 19

a) Daily estimates in summer period.

b. Location	Species	Seagrass	Epiphytes	Benthic micro-algae	Macro-algae	Phytoplankton	Reference
Europe	Cymodocea	400-700	---	---	375	---	Gessner and Hammer 1960
Alaska	Zostera						
Kinzarof		1500	---	---	393		McRoy 1970
Klawak		415	---	---	29		
Others		113	---	---	2.4		
N.Carolina	Zostera	80	25	---	---	---	Penhale 1977
Ches. Bay	P.pectinatus	20-60	0.1-0.6	---	---	---	Staver et al. 1981
	P.perfoliatus	20-80	0.1-0.6	---	---	---	Staver et al. 1981

(from USEPA 1982)

3 ppt
- Najas guadalupensis (southern naiad)

3-5 ppt
- Chara spp. (muskgrass)
- Vallisneria americana (wildcelery)

12-13 ppt
- Elodea canadensis (elodea)
- Myriophyllum spicatum (Eurasian watermilfoil)
- Ceratophyllum demersum (coontail)

20-25 ppt
- Potamogeton perfoliatus (redhead grass)
- Potamogeton pectinatus (sago pondweed)
- Zannichellia palustris (horned pondweed)

over 30 ppt
- Ruppia maritima (widgeongrass)
- Zostera marina (eelgrass)

The depth at which vegetation is able to survive is directly related to the penetration of incident radiation. Plants need light for photosynthesis, therefore turbidity affects their distribution by decreasing the amount of sunlight reaching greater depths. Temperature also affects the distribution of SAV, and exerts considerable influence upon its vegetative growth and flowering. These factors are considered in more detail in Appendix C for several east-coast species.

Three associations of submerged aquatic vegetation were described for the Chesapeake Bay, based on their co-occurrence in mixed beds. The first association tolerates fresh to slightly brackish water (upper reaches of the Bay) and includes bushy pondweed, coontail, elodea (waterweed), and wildcelery. The middle reaches of the Bay have associations of widgeongrass, Eurasian watermilfoil, sago pondweed, redhead grass, horned pondweed, and wildcelery. Finally, in the lower reaches of the Bay, eelgrass and widgeongrass predominate. The kinds of submerged aquatic vegetation encountered in the Chesapeake Bay from 1971 to 1981 are listed in Table III-5.

The major species of SAV found on the eastern coast of the United States (their distribution, environmental tolerances and consumer utilization) are listed in Appendix C. The species that are especially important as food items for waterfowl are coontail, muskgrass, bushy pondweed, sago pondweed, redhead grass, widgeongrass and wildcelery. Grazing by waterfowl is a primary force in the management of aquatic vegetation. Some aquatic vegetation, although it provides protective cover for wildlife, is considered a nuisance because of excessive growth and clogging of waterways. Elodea, Eurasian watermilfoil, and sago pondweed are among those considered to be pest species.

Information concerning aquatic vegetation in southern U.S. estuaries is found in literature by Chabreck and Condrey 1979, Beal 1977, and Correll and Correll 1972.

TABLE III-5. A LISTING OF THE SUBMERGED AQUATIC VEGETATION ENCOUNTERED IN THE CHESAPEAKE BAY FROM 1971 TO 1981.

Species	Vascular Plants[1]	Macro-Algae[1]
1. Redhead grass (*Potamogeton perfoliatus*)	X	
2. Widgeongrass (*Ruppia maritima*)	X	
3. Eurasian watermilfoil (*Myriophyllum spicatum*)	X	
4. Eelgrass (*Zostera marina*)	X	
5. Sago pondweed (*P. pectinatus*)	X	
6. Horned-pondweed (*Zanichellia palustris*)	X	
7. Wildcelery (*Vallisneria americana*)	X	
8. Common elodea (*Elodea canadensis*)	X	
9. Naiad (*Najas guadalupensis*)	X	
10. Muskgrass (*Chara spp.*)		X
11. Slender pondweed (*P. pusillus*)	X	
12. Coontail (*Ceratophyllum demersum*)	X	
13. Unidentified fragments	X	
14. Curly pondweed (*Potamogeton crispus*)	X	
15. Sea lettuce (*Ulva spp.*)		X
16. *Agardhiella spp.*		X
17. Unidentified filamentous green algae		X
18. Unidentified green algae		X
19. *Gracilaria spp.*	X	
20. Water-stargrass (*Heteranthera dubia*)	X	
21. Unidentified alga		X
22. *Enteromorpha spp.*		X
23. *Ceramium*		X
24. *Polysiphonia*		X
25. *Dasya spp.*		X
26. Unidentified red alga		X
27. Unidentified brown alga		X
28. *Champia parvula*		X

[1] An "X" in the column indicates the type of SAV.

(from USEPA 1982)

Adverse Impacts on SAV

Portions of the estuary may become enriched beyond their flushing and assimilative capacity and elevated levels of nitrogen and phosphorus begin to support abnormal algal growth and eutrophic conditions. Algal growths are important because they act to diminish to penetration of sunlight into the water. Submerged aquatic vegetation is dependent upon sunlight for photosynthesis, and when light penetration is diminished too much by algal growths, the SAV will be affected. These factors are discussed in detail in Chapter II.

Runoff may also introduce herbicides to the estuarine ecosystem. The magnitude of detrimental effects depends upon the particular herbicide, and its persistence in the environment and potential for leaching. Furthermore, several herbicides have a synergistic effect along with nutrients, its potential for leaching and persistence in the environment. Several pathogens may attack and diminish the size of submerged aquatic vegetation beds. Rhizoctonia solani is a fungus that attacks the majority of duck food plants, but is especially pathogenic to sago pondweed (Stevenson and Confer 1978). Lake Venice Disease causes a gradual wasting away of the host plant; it is manifested as a brownish, silt-like coating on leaves and stems. Milfoil is attacked by the Northeast Disease, which gradually causes the leaves to break off, leaving a blackened stem.

Survey Techniques

Aerial, surface and subsurface methods are used to prepare maps delineating vegetation types and percent cover. Plant growth stage (e.g. season) is critical when planning a plant survey. For example, early summer is the optimum time of year to record maximum plant coverage in the Chesapeake Bay but a different time of year may be more appropriate in other parts of the Country. Water transparency is also important to show plant growth. Aerial methods are useful in determining the distribution of plant associations, irregular features, normal seasonal changes and perturbations caused by pollutants. Mapping cameras are designed to photograph large areas without distortion. Areas of SAV beds may be derived from topographic quadrangles (Raschke 1983). The Earth Resources Observation System (EROS) Data Center may be used to obtain listings and photographs already available for a particular area.

Surface or ground maps can be prepared if the area is relatively small. Distances can be determined by ruled tapes, graduated lines, range finders, or, if more accuracy is required, surveyor's tools. Field observations of species may be supplemented by photographs. Divers can mark subsurface beds with bouys to facilitate determination of bed shapes and areas from the surface.

Regional surveys of flora give qualitative information, based upon visual observation and collection of plant types. To obtain more quantitative information, line transects, belt transects, or quadrats may be employed (Raschke 1983). Use of line transects involves placement of a weighted nylon or lead cord along a compass line and recording plant species and linear distance occupied. A belt transect can be treated as a series of quadrats, with each quadrat defined as the region photographed from a standard height or a marked area. The technique of sampling within a quadrat or plot of standard size is applicable to shallow and deep water. Where visibility is poor, epibenthic samplers can be used.

A fundamental characteristic of the community structure of submerged aquatic vegetation is the leaf area index (LAI). It is defined as the amount of photosynthetic surface per unit of biomass (U.S. EPA 1982). The photosynthetic area is measured by obtaining a two-dimensional outline of the frond, and determining the area with a planimeter. Leaf area index differences demonstrate the importance of light in regulating SAV communities and their adaptability to different light regimes. The greatest LAI values occur for mixed beds of Zostera and Ruppia; lower values were found for pure stands of Zostera and Ruppia (U.S. EPA 1982).

The information presented here is a brief overview of survey techniques used in the sampling of SAV. Supplementary discussions are found in literature by Kadlec and Wentz (1974), and Down (1983).

ESTUARINE FISH

Systems of Classification

Various authors have attempted to devise systems to classify estuarine organisms. Because salinity is the most dominant physical factor affecting the distribution of organisms, it is often used as the basis for classification systems. McLusky (1971, 1981) divides estuarine organisms into the following categories:

1. Oligohaline organisms - The majority of animals living in rivers and other fresh waters do not tolerate salinities greater than 0.1 ppt but some, the oligohaline species, persist at salinities up to 5 ppt.

2. True estuarine organisms - These are mostly animals with marine affinities which live in the central parts of estuaries. Most of them are capable of living in the sea but are not found there, apparently because of competition from other animals.

3. Euryhaline marine organisms - These constitute the majority of organisms living in estuaries with their distribution ranging from the sea into the central part of estuaries. Many disappear by 18 ppt but a few survive at salinities down to 5 ppt.

4. Stenohaline marine organisms - These occur in the mouths of estuaries at salinities down to 25 ppt.

5. Migrants - These animals, mostly fish and crabs, spend only a part of their life in estuaries with some, such as flounder (Platichthys) feeding in estuaries, and others, such as salmon (Salmo salar) or eels (Anguilla anguilla) using estuaries as routes to and from rivers and the sea.

A similar scheme of classification, shown in Table III-6, was defined by Remane. Components of fauna are separated according to the sources from which they arrived at their present-day habitat, e.g., from the sea, from freshwater and from the land. Marine and freshwater components are further divided based on salinity tolerances. The terrestrial component may be subdivided into those species which escape the effects of immersion by moving upwards when the tide floods the upper shore, and those species which remain on the shore and are able to survive submersion for several hours.

Day (1951, cited by Haedrich 1983) divided estuarine fishes into five categories: freshwater fishes found near the head of the estuary, stenohaline marine forms from the seaward end of the estuary, euryhaline marine forms occurring over wide areas, the truly estuarine fishes found only in the estuary, and migratory forms that either pass through the estuary or enter it only occasionally. A modified version of this classification was presented by McHugh (1967). His categories were:

1. Freshwater fish species that occasionally enter brackish waters.

2. Truly estuarine species which spend their entire lives in the estuary.

3. Anadromous and catadromous species.

4. Marine species which pay regular seasonal visits to the estuary, usually as adults.

5. Marine species which use the estuary primarily as a nursery ground, usually spawning and spending much of their adult life at sea, but often returning seasonally to the estuary.

6. Adventitious visitors which appear irregularly and have no apparent estuarine requirements.

Day's classification of biota and the Venice System of dividing estuaries into six salinity ranges were combined by Carriker (1967) to develop Table III-7. The right half of the table shows the biotic categories and the approximate penetration of animals relative to salinity zones in the estuary.

Salinity Preferences

Some freshwater fish species may occasionally stray into brackish waters. White catfish (*Ictalurus catus*) is a salt-tolerant freshwater form found in estuaries along the east coast of the United States. Three other species that are primarily freshwater, but have been captured in higher salinity areas are longnose gar (*Lepisosteus osseus*), bluegill (*Lepomis macrochirus*) and the flier (*Centrarchus macropterus*) (McHugh 1967).

Very few fish are considered to be truly estuarine. McHugh (1967) mentions only two species that he considers endemic to the estuarine environment. They are the striped killifish (*Fundulus majalis*) and the skilletfish

TABLE III-6. SUMMARY OF THE COMPONENTS OF AN ESTUARINE FAUNA

I. MARINE COMPONENT

The stenohaline marine component, not penetrating below 30 ppt
The euryhaline marine component

First grade, penetrate to 15 ppt
Second grade, penetrate to 8 ppt
Third grade, penetrate to 3 ppt
Fourth grade, penetrate to below 3 ppt

Brackish water component, lives in estuaries, but not in sea

II. FRESHWATER COMPONENT

The stenohaline freshwater component, not penetrating above 0.5 ppt
The euryhaline freshwater component

First grade, penetrate to 3 ppt
Second grade, penetrate to 8 ppt
Third grade, penetrate above 8 ppt

Brackish water component, lives in estuaries, but not in freshwater

III. MIGRATORY COMPONENT migrates through estuaries from sea to freshwater or vice versa

Anadromous, ascending rivers to spawn
Catadromous, descending to the sea to spawn

IV. TERRESTRIAL COMPONENT

Tolerant of Submersion
Intolerant of Submersion

(from Green 1967)

TABLE III-7. CLASSIFICATION OF ESTUARINE ZONES RELATING THE VENICE SYSTEM CLASSIFICATION TO DISTRIBUTIONAL CLASSES OF ORGANISMS.

	Venice System		Ecological Classification				
Divisions of Estuary	Salinity Ranges 0/00	Zones	Types of Organisms and Approximate Range of Distribution in Estuary, Relative to Division and Salinities				
River	0.5	Limnetic		Limnetic			
Head	0.5-5	Oligohaline		Oligohaline			
Upper Reaches	5-18	Mesohaline	Mixohaline				
Middle Reaches	18-25	Polyhaline			True estuarine (estuarine endemics)		
Lower Reaches	25-30	Polyhaline					
Mouth	30-40	Euhaline		Stenohaline marine		Euryhaline marine	Migrants

(from Carriker 1967)

(Gobiesox strumosus). The fourspine stickleback (Apeltes quadracus) is a small fish that is abundant in estuaries but cannot be considered truly estuarine because it enters freshwater occasionally. Beccasio et al. (1980) included killifish, silverside, anchovy and hogchoker in the category of truly estuarine species. Other authors concede the existence of truly estuarine species although they fail to mention them as such. Instead, fish are categorized as spending a major portion of their life cycle in an estuary, as being dependent on the estuary at some time, or as being the dominant species present.

A listing of species commonly found in North American Atlantic/Gulf coast estuaries and their salinity tolerances/preferences as adults is contained in Table III-8. It should be noted, however, that salinity preferences of some fish may change at the time of migration. For example, adult stickleback (Gasterosteus aculeatus) prefer freshwater in March and saltwater in June/July (McLusky 1971). Salinity tolerances also differ depending on the organism's stage of life. Salinity tolerances or requirements of juveniles may be unlike those of the adult.

The Gulf of Mexico estuaries support populations of fish that are also found along the Atlantic coast. For example, spot (Leiostomus xanthurus) are abundant along the Gulf and the Atlantic coasts. The Atlantic croaker ranges from the New England States to South America, although it is basically a southern species important in the Gulf of Mexico and South Atlantic Bight. Gulf menhaden is an estuarine dependent species that primarily inhabits northern Gulf of Mexico waters. Southern kingfish (Menticirrhus americanus) have been collected along the coasts from Long

TABLE III-8. SALINITY TOLERANCE/PREFERENCE OF CERTAIN FISHES FOUND IN ATLANTIC/GULF COAST ESTUARIES

Scientific Name	Common Name	Salinity (ppt) (Tolerance/Preference)
Alosa spp.	Herring, shad, alewife	0-34/-
Brevoortia patronus	Gulf menhaden	5-35/5-10
Brevoortia tyrannus	Atlantic menhaden	1-36/5-18
Cynoscion regalis	Weakfish	-/10-34
Ictalurus catus	White catfish	<14.5/-
Ictalurus punctatus	Channel catfish	<21/<1.7
Leiostomus xanthurus	Spot	3-34/-
Menidia menidia	Atlantic silverside	0-35/-
Micropogonias undulatus	Atlantic croaker	0-40/10-34
Morone americana	White perch	0-30/4-18
Morone saxatilis	Striped bass	0-35/>12
Perca flavescens	Yellow Perch	0-13/5-7
Pomatomus saltatrix	Bluefish	7-34/-

(from U.S. EPA, 1983a)

Island Sound, New York, to Port Isabel, Texas (Sikora and Sikora 1982). They are estuarine dependent, and larval southern kingfish move from offshore spawning areas to estuarine nursery areas. Salinity preferences of southern kingfish varies with size. Only the smaller juveniles are found in waters with salinities of less than 10 ppt. Larger juveniles (>150 mm or 5.9 inches standard length, SL) are rarely taken in waters with salinities less than 20 ppt, and are usually found in deeper waters such as sounds, near the mouths of passes, or near barrier islands (Sikora and Sikora 1982). The most common fish found in Gulf of Mexico estuaries are listed in Table III-9, along with the range of salinities in which they were captured (Perret et al. 1971). Additional information on the environmental requirements of Gulf coast species is presented in Appendix D.

Appendix B contains a listing of habitat requirements of major Atlantic coast estuarine species during their life cycles. More detailed descriptions of habitat requirements of egg, larval and juvenile stages of fishes of the Mid-Atlantic bight are contained in several publications by the United States Fish and Wildlife service (1978, Volumes I-VI). Mansueti and Hardy (1967) also published information regarding fishes of the Chesapeake Bay region. These reports contain illustrations of the life stages for many species, along with pertinent information regarding preferred substrate, salinity and temperature. Although the books focus on egg, larval, and juvenile stages, the adult stage is also addressed.

Annual Cycles of Fish in Estuaries

Annual cycles and abundances of species are important in the ecology of estuaries. The composition of the estuarine fauna varies seasonally, reflecting the life histories of species. Anadromous fishes pass through

TABLE III-9. FISHES COLLECTED IN SAMPLES IN LOUISIANA ESTUARIES

Scientific Name	Common Name	Salinity (ppt) range at collection sites / range where greatest number of individuals captured
Anchoa hepsetus	Striped anchovy	7.0-29.9/>15.0
Anchoa mitchilli	Bay anchovy	0-31.5/-
Arius felis	Sea catfish	0->30.0/>10.0
Bagre marinus	Gafftopsail catfish	0-29.9/>5.0
Brevoortia patronus	Menhaden	0-30.0/5.0-24.9
Citharichthys spilopterus	Bay whiff	0->30.0/>15.0
Cynoscion nebulous	Spotted seatrout	0.2-30.0/>15.0
Dorosoma cepedianum	Gizzard shad	0-29.9/<10.0
Dorosoma pentenense	Threadfin shad	0-29.9/<5.0
Fundulus similis	Longnose killifish	0.5-30.7/>10.0
Ictalurus furcatus	Blue catfish	0-4.9/-
Leiostomus xanthurus	Spot	0.2->30.0/>10.0
Membras martinica	Rough silverside	2.0-29.9/>10.0
Menidia beryllina	Tidewater silverside	0->30.0/-
Menticirrhus americanus	Southern kingfish	2.0->30.0/>10.0
Micropogonias undulatus	Atlantic croaker	0->30.0/-
Mugil cephalus	Striped mullet	0->30.0/5.0-19.9
Paralichthys lethostigma	Southern flounder	0->30.0/-
Polydactylus ocfonemus	Atlantic threadfin	1.6-29.9/-
Prionotus tribulus	Bighead searobin	2.0->30.0/>15.0
Sciaenops ocellatus	Red drum	5.0-29.9/-
Sphaeroides nephelus	Southern puffer	1.7-30.9/>10.0
Synodus foetens	Inshore lizardfish	4.0-30.9/>10.0
Trinectes maculatus	Hogchoker	1.7-30.9/>10.0

(from Perret et al. 1971)

estuaries on the way to spawning grounds. In the Gulf of Mexico, the Alabama shad and the striped bass are important anadromous species (Beccasio et al. 1982). Both species are sought for sport. Anadromous species on the Pacific coast include chinook salmon, chum salmon, pink salmon, sockeye salmon, Dolly Varden, river lamprey and cutthroat trout (Beccasio et al. 1981, Beauchamp et al. 1983). Studies have shown that temperature is an important factor governing the timing of migrations and spawning for some species. Chinook salmon (Oncorhynchus tshawytscha) will not migrate when temperatures rise above 20°C. American shad live most of their lives at sea, but pass through estuaries to spawn in fresh water. Spawning of shad is dependent on temperature, and commences when the maximum daily water temperature reaches 16°C. It continues to about 24°C, peaking at 21°C (Jones and Stokes Assoc. 1980). Additional information on Pacific fishes is available in Hart (1973). Life history is presented along with certain environmental requirements of the species. However, salinity tolerances and preferences are noted infrequently.

Many of these anadromous species are major sport and commercial fish. Striped bass, for example, occur along the east coast of North America from the St. Lawrence River, Canada, to the St. Johns River, Florida; along the Gulf of Mexico; and from the Columbia River, Washington to Ensenada, Mexico, along the Pacific Coast (Bain and Bain 1982). Temperature was cited as a key factor in their distribution. Striped bass migrate to fresh or nearly fresh water to spawn. The optimum temperature for egg survival is 17° to 20°C. A minimum water velocity of 30 cm/s (1 fps) is necessary to prevent eggs from resting on the bottom. After hatching, the larvae remain in nearly fresh water. Striped bass larvae need a minimum of 3 mg/l dissolved oxygen. Optimum survival of larvae occurs when the temperature is between 18°C and 21°C (12°-23°C tolerated) and salinity ranges from 3-7 ppt (0-15 ppt tolerated). Juveniles are more tolerant of environmental conditions and migrate to higher salinity portions of the estuary, feeding on small prey fish. Optimum temperatures for juveniles are between 14°C and 21°C, but a range of 10°C to 27°C can be tolerated. Some adult striped bass may remain in estuaries, while others may embark on coastal migrations. Striped bass populations from Cape Hatteras, North Carolina to New England may travel substantial distances along the coast, while populations in the southern portion of the range and on the Pacific Coast tend to remain in the estuary or in offshore waters nearby (Bain and Bain 1982). It should also be noted that preferred temperatures vary depending on ambient acclimation temperatures. Striped bass acclimated to 27°C in late August avoided waters of 34°C, while 13°C was avoided by striped bass acclimated to 5°C in December.

Salmonids, numerous flatfishes and sturgeon are dependent upon Pacific coast estuaries at some time during their life cycles. For example, chum salmon spawn in rivers from northern California to the Bering Sea during October through December. Adults die after spawning. The young hatch in spring, and move to estuaries and bays where they remain for 3 to 4 months. They move to deeper waters gradually, as they grow (Beccasio et al. 1981). The sand sole, a sport species along the northwest Pacific coastline, spends up to its first year in bays and estuaries.

Some fish species utilize estuaries primarily as nursery grounds. Young fishes feed in the productive estuarine system and then migrate seaward or

TABLE III-10. FISHES THAT USE ESTUARIES PRIMARILY AS NURSERY AREAS

Scientific Name	Common Name
Alosa aestivalis	Blueback herring
Alosa pseudoharenga	Alewife
Brevoortia patronus	Gulf menhaden
Brevoortia tyrannus	Atlantic menhaden
Clupea harengus	Atlantic herring
Clupea harengus pallasii	Pacific herring
Cottus asper	Prickly culpin
Cynoscion regalis	Weakfish
Leiostomus xanthurus	Spot
Micropogonias undulatus	Atlantic croaker
Morone americana	White perch
Morone saxatilis	Striped bass
Mugil cephalus	Mullet (striped)
Mugil curema	Mullet (white)
Oncorhynchus gorbuscha	Pink salmon
Oncorhynchus kisutch	Coho salmon
Osmerus mordax	Rainbow smelt
Perca flavescens	Yellow perch
Platichthys stellatus	Starry flounder
Pseudopleuronectes americanus	Winter flounder
Salmo salar	Atlantic salmon
Trinectes maculatus	Hogchoker

(from U.S. EPA 1982, Jones and Stokes Assoc. 1981, Haedrich 1983, Beccasio et al. 1980)

towards freshwater. Most of the fishes using estuaries as a nursery area are anadromous, the adults being principally marine. Table III-10 lists anadromous fishes (from both the east and west coasts of North America) which use estuaries primarily as nursery grounds. Although Table III-10 is not a comprehensive listing, it contains those fishes mentioned most frequently in the literature (U.S. EPA 1983a, Jones and Stokes Assoc. 1981, Haedrich 1983, Beccasio et al. 1980).

White perch (Morone americana), another commercially important fish, is also abundant in estuaries on the east coast of North America. Populations in the Chesapeake Bay area have been observed to inhabit the various tributaries, with some fish entering the Bay itself. The American eel (Anguilla rostrata) is the only catadromous species noted in the literature. It spawns in the Sargasso Sea, then migrates to and lives in estuaries or freshwaters for several years before returning to the sea.

Some fish take advantage of the complex circulation pattern of estuaries, spawning in offshore areas to allow eggs or larvae to drift up into the estuary. Most notably, the young of flatfishes (winter and starry flounder) and some of the drums (croaker, weakfish and spot) utilize the estuarine circulation system (U.S. Dept. of Interior 1970). The juveniles then feed and mature within the estuary. The gulf menhaden (Brevoortia patronus) supports the largest commercial fishery by weight (Christmas et al. 1982). It is an estuarine-dependent marine species that is found primarily in northern Gulf of Mexico waters. Gulf menhaden spawn from mid-October through March in marine waters. Currents transport planktonic larvae to estuarine areas, where they transform into juveniles. As they grow, juveniles migrate to deeper, more saline waters. Juveniles are able to tolerate water temperatures from 5°C to 34°C. Adults and juveniles may inhabit estuaries throughout the year. The Atlantic croaker also uses the estuary as a nursery area. Juveniles reside in salinities from 0.5 to 12 ppt, moving to higher salinity waters as they grow. They tolerate a wide range of temperatures, from 6°C to 20°C. The spot (Leiostomus xanthurus) is also estuarine dependent. Adults spawn in nearshore marine waters, but juveniles spend much of their lives in estuaries. Juvenile spot tolerate temperatures from 1.2°C to 35.5°C, preferring a range of 6°C to 20°C. They have been collected in salinities from 0 to 60 ppt, but tend to concentrate near the saltwater-freshwater boundary (Stickney and Cuenco 1982). Other estuarine-dependent species in the Gulf of Mexico are the bay anchovy, sea catfish, gafftopsoil catfish, spotted and sand seatrout, red drum, black drum, southern kingfish and southern flounder.

Some marine species enter the estuary seasonally. The spotted hake (Urophycis regins) enters the Chesapeake Bay in late fall, and exits before the warm weather. In Texas estuaries, Urophycis floridanus follows a similar migration pattern.

The bluefish (Pomatomus saltatrix) is often considered an adventitious visitor to Atlantic coast estuaries (McHugh 1967). Although the bluefish is a seasonal visitor, it may not appear if environmental conditions are not suitable. Other species may occasionally enter estuaries to feed on small fish, or if environmental conditions are suitable.

Difficulties often arise because sufficient information is not available on the life cycles of certain species to enable their classification. For this reason, and because of the many species of fish that enter estuaries only occasionally, a fully comprehensive list of species is not available. However, Haedrich (1983) compiled a listing of characteristic families found in estuaries, based upon faunal lists reported in various papers. He divided the fauna into families found in three zones, that of temperate, tropics/subtropics, and high latitudes. The families in Table III-11 include the few resident species, anadromous fish and marine species that utilize the estuary as feeding and nursery areas.

Habitat Suitability Index Models

Habitat Suitability Index (HSI) models developed by the U.S. Fish and Wildlife Service consider the quality of habitats necessary for specific species during each life stage. The variables selected for study in a given model are known to affect species growth, survival, abundance, standing crop and distribution. Output from the models is used to determine the quantity of suitable habitat for a species. The HSI values produced by the models are relative, and should be used to compare two areas, or the same area at different times. Thus, the area with the greater HSI value is interpreted to have the potential to support a greater number of a species than that with the lower HSI. Values range from 0 to

TABLE III-11. CHARACTERISTIC FAMILIES OF ESTUARINE SYSTEMS

High Latitudes	Tropics/Subtropics
Salmonidae (salmon and trout)	Clupeidae (herrings)
Osmeridae (smelt and capelin)	Engraulidae (anchovies)
Gasterosteidae (sticklebacks)	Chanidae (milkfish)
Ammodytidae (sand lance)	Synodontidae (lizardfish)
Cottidae (sculpins)	Belonidae (silver gars)
	Mugilidae (mullets)
Temperate Zones	Polynemidae (threadfins)
Anguillidae (freshwater eels)	Sciaenidae (crockers)
Clupeidae (herrings)	Gobiidae (gobies)
Engraulidae (anchovies)	Cichlidae (cicheids)
Ariidae (saltwater catfishes)	Soleidae (flounders)
Cyprinodontidae (killifishes)	Cynoglossidae (flounders)
Gadidae (cods)	
Gasterosteidae (sticklebacks)	
Serranidae (basses)	
Sciaenidae (croakers)	
Sparidae (seabreams)	
Pleuronectidae (flounders)	

(from Haedrich 1983)

1, with 1 representing the most suitable conditions. HSI models can be used to provide one value for all life stages, or to calculate HSI values for each component (e.g. spawning, egg, larvae, juvenile, adult). There is some uncertainty in the use of the HSI models, both in the form of calculation and the fact that they are unverified models. They have not been tested to see if they work. The form of calculation leads to the possibility of their being insensitive to environmental changes. An area may have undergone great degradation before the HSI model drops in value. More information concerning HSI models can be found in Chapter IV-1 of the Technical Support Manual (U.S. EPA 1983b). Models are currently available for the following estuarine fish: striped bass (Bain and Bain 1982), juvenile Atlantic croaker (Diaz 1982), Gulf menhaden (Christmas et al. 1982), juvenile spot (Stickney and Cuenco 1982), Southern kingfish (Sikora and Sikora 1982), and alewife and blueback herring (Pardue 1983). Models have been developed for several other estuarine organisms. They are northern Gulf of Mexico brown shrimp and white shrimp (Turner and Brody 1983), Gulf of Mexico American oyster (Cake 1983), and littleneck clam (Rodnick and Li 1983).

SUMMARY

The preceding sections touch upon procedures that might be used and specific phenomena that might be evaluated during the field collection phase of a waterbody survey.

Strong seasonal changes in estuarine biological communities compound difficulties involved in collection of useful data. Because of annual cycles, important organisms can be totally absent from the estuaries for portions of the year, yet be dominant community members at other times. For example, brown and white shrimp spend part of the year in estuaries, and migrate to deeper, more saline waters as the season progresses. Furthermore, estuarine biological communities may also vary from year to year. Although it has not been mentioned explicitly, it is understood that, if at all possible, a reference site will have been identified and will have been studied in a manner that is consistent with the study of the estuary of interest. In addition to whatever field data is developed on the estuary and its reference site, it is also important to examine whatever information might exist in the historical record.

The importance of submerged aquatic vegetation has not been fully discussed in this Chapter, nor have any tools been presented by which to digest all the assessments so far presented. This will be done in Chapter IV, Interpretation.

CHAPTER IV

SYNTHESIS AND INTERPRETATION

INTRODUCTION

The basic physical and chemical processes of the estuary are introduced in Chapter II, with particular emphasis placed on a description of stratification and circulation in estuarine systems, on simplifying assumptions that can be made to characterize the estuary, on desktop procedures that might be used to define certain physical properties, and on mathematical models that are suitable for the investigation of various physical and chemical processes.

The applicability of desktop analyses or mathematical models will depend upon the level of sophisticaton required for a particular use attainability study. These types of analysis are important to the study in three ways: to help segment the estuary into zones with homogeneous physical characteristics, to help in the selection of a suitable reference estuary, and to help in the analysis of pollutant transport and other phenomena in the study area. Several case studies are presented to illustrate the use of measured data and model projections in the use attainability study. The selection of a reference estuary(ies) is discussed later in this Chapter.

Chapter II also offers a discussion of chemical phenomena that are particularly important to the estuary: the several factors that influence dissolved oxygen concentrations in surface and bottom layers and the impact of nutrient overenrichment on submerged aquatic vegetation (SAV). Other chemical evaluations are discussed in the Technical Support Manual (EPA, November 1983).

The biological characteristics of the estuary are summarized in Chapter III. Specific information on various species common to the estuary are presented to assist the investigator in determining aquatic life uses. Typical forms of estuarine flora and fauna are described and the overall importance of SAVs--as an indicator of pollution and as a source of habitat and nutrient for the biota--for the use attainability study is emphasized.

In this Chapter, emphasis is placed on a synthesis of the physical, chemical and biological evaluations which will be performed, to permit an overall assessment of uses, and of use attainability in the estuary. Of particular importance are discussions of the selection and analysis of a reference site, and the statistical analysis of the data that are developed during the use study.

USE CLASSIFICATIONS

There are many use classifications-navigation, recreation, water supply, the protection of aquatic life-which might be assigned to a water body. These need not be mutually exclusive. The water body survey as discussed in this volume is concerned only with aquatic life uses and the protection of aquatic life in a water body. Although the term "aquatic life" usually refers only to animal forms, the importance of submerged aquatic vegetation

(SAV) to the overall health of the estuary dictates that a discussion of uses include forms of plant life as well.

The use attainability analysis may also be referred to as a water body survey. The objectives in conducting a water body survey are to identify:

1. The aquatic life uses currently being achieved in the water body,

2. The potential uses that can be attained, based on the physical, chemical and biological characteristics of the water body, and

3. The causes are of any impairment of uses.

The types of analyses that might be employed to address these three points are summarized in Table IV-1. Most of these are discussed in detail elsewhere in this volume, or in the Technical Support Manual.

Use classification systems vary widely from State to State. Use classes may be based on geography, salinity, recreation, navigation, water supply (municipal, agricultural, or industrial), or aquatic life. Clearly, little information is required to place a water body into such broad categories. Far more information may be gathered in a water body survey than is needed to assign a classification, based on existing State classifications, but the additional data may be necessary to evaluate management alternatives and refine use classification systems for the protection of aquatic life in the water body.

Since there may not be a spectrum of aquatic protection use categories available against which to compare the findings of the biological survey; and since the objective of the survey is to compare existing uses with designated uses, and existing uses with potential uses, as seen in the three points listed above, the investigators may need to develop their own system of ranking the biological health of a water body (whether qualitative or quantitative) in order to satisfy the intent of the water body survey. Implicit in the water body survey is the development of management strategies or alternatives which might result in enhancement of the biological health of the water body. To do this it would be necessary to distinguish the predicted results of one strategy from another, in cases where the strategies are defined in terms of aquatic life protection.

The existing state use classifications may not be helpful at this stage, for one may very well be seeking to define use levels within an existing use category, rather than describing a shift from one use classification to another. Therefore, it may be helpful to develop an internal use classification system to serve as a yardstick during the course of the water body survey, which may later be referenced to the legally constituted use categories of the state.

A scale of biological health classes is presented in Table IV-2. This is a modified version of Table V-2 presented in the Technical Support Manual, and it offers general categories against which to assess the biology of an estuary. The classification scheme presented in Table IV-3, which was developed in conjunction with extensive studies of the Chesapeake Bay, associates biological diversity with various water quality parameters. The Toxicity Index (T_I) in the table was discussed in Chapter III.

Table IV-1. SUMMARY OF TYPICAL ESTUARINE EVALUATIONS (adapted from EPA 1982, Water Quality Standards Handbook)

PHYSICAL EVALUATIONS	CHEMICAL EVALUATIONS	BIOLOGICAL EVALUATIONS
° Size (mean width/depth)	° Dissolved oxygen	° Biological inventory (existing use analysis)
° Flow/velocity	° Toxics	° Fish
° Total volume		- macroinvertebrates
° Reaeration rates	° Nutrients	- microinvertebrates
		° Plants
	- nitrogen	- phytoplankton
° Temperature	- phosphorus	- macrophytes
° Suspended solids	° Chlorophyll-a	
° Sedimentation	° Sediment oxygen demand	° Biological condition/ health analysis
		- diversity indices
° Bottom stability	° Salinity	- tissue analyses
° Substrate composition and characteristics	° Hardness	- Recovery Index
	° Alkalinity	
° Channel debris	° pH	° Biological potential analysis
° Sludge/sediment	° Dissolved solids	
° Riparian characteristics		- reference reach comparison

TABLE IV-2. BIOLOGICAL HEALTH CLASSES WHICH COULD BE USED IN WATER BODY ASSESSMENT (Modified from Karr, 1981)

Class	Attributes
Excellent	Comparable to the best situations unaltered by man; all regionally expected species for the habitat including the most intolerant forms, are present with full array of age and sex classes; balanced trophic structure.
Good	Fish invertebrate and macroinvertebrate species richness somewhat less than the best expected situation; some species with less than optimal abundances or size distribution; trophic structure shows some signs of stress.
Fair	Fewer intolerant forms of plants, fish and invertebrates are present.
Poor	Growth rates and condition factors commonly depressed; diseased fish may be present. Tolerant macroinvertebrates are often abundant.
Very Poor	Few fish present, disease, parasites, fin damage, and other anomalies regular. Only tolerant forms of macroinvertebrates are present.
Extremely Poor	No fish, very tolerant macroinvertebrates; or no aquatic life.

TABLE IV-3. A FRAMEWORK FOR THE CHESAPEAKE BAY ENVIRONMENTAL QUALITY CLASSIFICATION SCHEME

Class	Quality	Objectives	Quality	T_I	T_N	T_P
A	Healthy	supports maximum diversity of benthic resources, SAV, and fisheries	Very low enrichment	1	<0.6	<0.08
B	Fair	moderate resource diversity, reduction of SAV, chlorophyll occasionally high	moderate enrichment	1-10	0.6-1.0	0.08-0.14
C*	Fair to Poor	a significant reduction in resource diversity, loss of SAV, chlorophyll often high, occasional red tide or blue-green algal blooms	high enrichment	11-20	1.1-1.8	0.15-0.20
D	Poor	limited pollution-tolerant resources, massive red tides or blue-green algal blooms	significant enrichment	>20	>1.8	>0.20

Note: T_I indicates Toxicity Index
T_N indicates Total Nitrogen in mg l^{-1}
T_P indicates Total Phosphorus in mg l^{-1}

* Class C represents a transitional state on a continuum between classes B and D.

ESTUARINE AQUATIC LIFE PROTECTION USES

Even though the estuary characteristically supports a lesser number of species than the adjacent freshwater or marine systems, it may be considerably more productive. Accordingly, uses might be defined so as to recognize specific fisheries (and the different conditions necessary for their maintenance), and to recognize the importance of the estuary as a nursery ground and a passageway for anadromous and catadromous species. Currently the water body use classification systems of the coastal states distinguish between marine and freshwater conditions, occasionally between tidal and freshwater conditions, but seldom make reference to the estuary. Uses and standards written for marine waters presumably are intended to apply to estuarine waters as well.

It is common in these States to include as a use of marine or tidal waters the harvesting and propagation of shellfish, frequently with reference to the sanitary and bacteriological standards included in National Shellfish Sanitation Program Manual of Operations: Part 1, Sanitation of Shellfish Growing Areas, published by the Public Health Service (1965). The term shellfish applies to both molluscs and crustaceans. Other marine protection uses which may be applicable to the estuary are worded in terms such as the growth and propagation of fish and other aquatic life, preservation of marine habitat, harvesting for consumption of raw molluscs or other aquatic life, or preservation and propagation of desirable species.

In establishing a set of uses and associated criteria to be used in the water body survey, the investigator might wish to consider examples like the State of Florida's criteria for Class II (Shellfish Propagation or Harvesting) and Class III (Propagation and Maintenance of a Healthy, Well-Balanced Population of Fish and Wildlife) Waters published in the Water Quality Standards of the Florida Department of Environmental Regulation. The published criteria are extensive and include the following categories which are of importance to the estuarine water body survey:

Biological Integrity - the Shannon-Weaver diversity index of benthic macroinvertebrates shall not be reduced to less than 75 percent of established background levels as measured using organisms retained by a U.S. Standard No. 30 sieve and collected and composited from a minimum of three natural substrate samples, taken with Ponar type samplers with minimum sampling areas of 225 square centimeters.

Dissolved Oxygen - the concentration in all waters shall not average less than 5 milligrams per liter in a 24-hour period and shall never be less than 4 milligrams per liter. Normal daily and seasonal fluctuations above these levels shall be maintained.

Nutrients - In no case shall nutrient concentrations of a body of water be altered so as to cause an imbalance in natural populations of aquatic flora or fauna.

SELECTION OF REFERENCE SITES

General Approach. There is a detailed discussion of the selection of reference or control sites in Chapter IV-6 of the Technical Support Manual. Although this discussion was prepared in the context of stream and lake studies, much of the material is pertinent to the study of estuaries as well. Riverine water body surveys may range in scale from a specific well-defined reach to perhaps an entire stream. One might expect to find a similar range of scale in estuary studies. The lateral bounds of the riverine study area generally are delineated by but not necessarily limited to the stream banks. The specification of a reference reach is prescribed by the scale of the study. If a short reach is under study, the reference reach might be designated upstream of the study area. If an entire river is under review, another river will have to be identified that will serve as an appropriate control.

An estuarine study may focus on a specific area, but the bounds of the study area are not easily defined because a physical counterpart to the river bank may not exist. Other factors compound the difficulties in designing an estuary study compared to the design of a river study. A major difference is that estuary segments cannot be so easily categorized because of seasonal changes in the salinity profile. Partitioning the estuary into segments with relatively uniform physical characteristics is an important first step of a water body survey.

It may be possible to study a small estuary as a single segment, but it will be necessary to go elsewhere for a reference site. This may be easily accomplished among the many bar built estuaries of the southeastern coast. For the large estuary, one may need only to examine a well-defined segment which has been affected by a point source discharge. If the segment is an embayment tributary to the main stem of the estuary, it may not be difficult to find a suitable control embayment within the same estuary. As the scale of the study increases, however, the difficulties associated with the establishment of a reference site also increases. It may not make sense to treat the entire estuary as a single unit for the use attainability survey, especially if use categories are associated with salinity ranges, different depths, etc. In such a case one would segment the estuary based upon physical characteristics such as salinity levels and circulation patterns, and then define the reference site in similar fashion. As a practical matter, it may not make sense to examine an entire estuary as a single unit, especially a large one. For example, the Chesapeake Bay has been subjected to a form of use attainability studies for a number of years at a cost of many millions of dollars. However, Chesapeake Bay is so complex that, despite the intensity of study, clear explanations are not always possible for the many undesirable changes that have taken place. The Chesapeake Bay itself is unique and no suitable reference estuary exists. From the use attainability standpoint, an estuary such as the Chesapeake or the Delaware or the Hudson is best broken down into segments that are homogeneous in characteristics and manageable in size.

Statistical Comparisons of Impact Sites With Control Sites. Reference site comparisons typically rely upon either parametric or nonparametric statistical tests of the null hypothesis to determine whether water quality or any other use attainment indicator at the impact site is significantly different from conditions at the control site(s).

Parametric statistics, which are suitable for datasets that exhibit a normal distribution, include the F (folded)-statistic on the difference between the variances at the impact site and control site and the t-statistic on the difference between the means. In order to conclude that there is no significant difference between the water quality conditions (or another indicator) at the impact site and the control site, both the F-statistic and the t-statistic should exhibit probabilities exceeding the 0.05 probability cutoff for the 95 percent confidence interval. In cases where the impact site is being compared with multiple control sites, parametric procedures such as the Student-Newman-Keuls (SNK) test, the least significant difference (LSD) test, and the Duncan's Multiple Range test can be used to test for differences among the grouped means.

Since water quality datasets are often characterized by small sample sizes and non-normal distributions, it is likely that nonparametric statistical tests may be more appropriate for the monitoring database. Nonparametric statistics assume no shape for the population distribution, are valid for both normal and non-normal distributions, and have a much higher power than parametric statistical techniques for analyses of datasets which are characterized by small sample sizes and skewed distributions. The one-sided Kolmogorov-Smirnov (K-S) test can be used to quantify whether each dataset is normally (or lognormally) distributed, thereby governing the selection of either parametric or nonparametric procedures. If nonparametric procedures are selected, significant differences in distributions can be evaluated with the two-sided K-S test, while significant differences in the central value can be tested with the Wilcoxon Ranksum test. Both nonparametric tests should exhibit probability values exceeding the cutoff for the 95 percent confidence interval in order to conclude that there is no significant difference in water quality conditions at the impact site and a control site. For comparisons with multiple control sites, nonparametric procedures such as the Kruskal-Wallis test and the Friedman Ranksum test can be used to test for significant differences among medians (if it can be assumed that the distributions of each dataset are not significantly different.

The same types of statistical tests can be used to evaluate sediment and biological monitoring data to determine whether suitable conditions for use attainability exist at the impact site. Either parametric or nonparametric statistical procedures can be used to compare conditions at the impact site and control site(s) which are unaffected by effluent discharge or other pollution sources. In cases where there are no statistically significant differences in distributions and/or control values, it may be assumed that sediment and/or biological monitoring results at the impact site and control site(s) are similar.

CURRENT AQUATIC LIFE PROTECTION USES

The actual aquatic protection uses of a water body are defined by the resident flora and fauna. The prevailing chemical and physical attributes will determine what biota may be present, but little need be known of these attributes to describe current uses. The raw findings of a biological survey may be subjected to various measurements and assessments, as discussed in Section IV (Biological Evaluations) of the Manual. After performing an inventory of the flora and fauna and considering a diversity index or other indices of biological health, one should be able adequately to describe the condition of the aquatic life in the water body.

CAUSES OF IMPAIRMENT OF AQUATIC LIFE PROTECTION USES

If the biological evaluations indicate that the biological health of the system is impaired relative to a "healthy" reference aquatic ecosystem (e.g., as determined by reference site comparisons), then the physical and chemical evaluations can be used to pinpoint the causes of that impairment. Figure IV-1 shows some of the physical and chemical parameters that may be affected by various causes of change in a water body. The analysis of such parameters will help clarify the magnitude of impairments to attaining other uses, and will also be important to the third step in which potential uses are examined.

ATTAINABLE AQUATIC LIFE PROTECTION USES

A third element to be considered is the assessment of potential uses of the water body. This assessment would be based on the findings of the physical, chemical and biological information which has been gathered, but additional study may also be necessary. A reference site comparison will be particularly important. In addition to establishing a comparative baseline community, defining a reference site can also provide insight into the aquatic life that could potentially exist if the sources of impairment were mitigated.

The analysis of all information that has been assembled may lead to the definition of alternative strategies for the management of the estuary at hand. Each such strategy corresponds to a unique level of protection of aquatic life, or aquatic life protection use. If it is determined that an array of uses is attainable, further analysis which is beyond the scope of the water body survey would be required to select a management program for the estuary.

One must be able to separate the effects of human intervention from natural variability. Dissolved oxygen, for example, may vary seasonally over a wide range in some areas even without anthropogenic effects, but it may be difficult to separate the two in order to predict whether removal of the anthropogenic cause will have a real effect. The impact of extreme storms on the estuary, such as Hurricane Agnes on the Chesapeake Bay in 1972, may completely confound our ability to distinguish the relative impact of anthropogenic and natural influences on immediate effects and longterm trends. In many cases the investigator can only provide an informed guess. Furthermore, if a stream does not support an anadromous fishery because of dams and diversions which have been built for water supply and recreational purposes, it is unlikely that a concensus could be reached to restore the fishery by removing the physical barriers -- the dams -- which impede the migration of fish. However, it may be practical to install fish ladders to allow upstream and downstream migration. Another example might be a situation in which dredging to remove toxic sediments may pose a much greater

SOURCE OF MODIFICATION

WATER QUALITY PARAMETERS

	Acid Mine Drainage or Acid Precipitation	Sewage Treatment Plant Discharge (primary or secondary)	Agricultural Runoff (pasture or cropland)	Urban Runoff	Channelization	(Industries) Pulp and Paper	Textile	Metal Finishing and Electroplating	Petroleum	Iron and Steel	Paint and Ink	Dairy and Meat Products	Fertilizer Production and Lime Crushing	Plastics and Synthetics
pH	D					C	I	C		D	C		D,I	C
Alkalinity	D						I						D,I	
Hardness	I						I						I	
Chlorides		I		I								I		
Sulfates	I								I	I			I	I
TDS	I						I		I		I		I	
TKN		I	I	I					I	I		I	I	I
NH_3-N		I							I	I			I	I
Total-P		I	I	I				I				I	I	
Ortho-P		I		I				I					I	
BOD_5		I				I	I		I	I	I	I		I
COD	I	I		I		I	I			I	I	I		I
TOC		I	I	I		I			I	I	I	I		I
COD/BOD_5	I			I		I	I		D	I				
D.O.		D				D						D		
Aromatic Compounds			I	I		I			I					I
Fluoride								I					I	I
Cr				I		I	I	I	I		I			I
Cu	I			I		I		I			I			I
Pb				I				I	I	I	I			
Zn	I			I		I		I	I	I	I			I
Cd		I		I				I			I			I
Fe	I			I				I		I	I		I	I
Cyanide										I				I
Oil and Grease						I	I	I	I	I	I	I		I
Coliforms	D	I	I	I				D		D	D	I		
Chlorophyll	D	I	I		I	D		D	D	D	D	I	I	D
Diversity	D	D		D	D	D	D	D	D	D	D			D
Biomass	D	I	I		I		I	D	D	D	D	I	I	D
Riparian Characteristics					C									
Temperature					I									
TSS			I	I	I	I	I	I			I		I	I
VSS				I		I								
Color						I	I				I	I		I
Conductivity	I												I	
Channel Characteristics					C									

Figure IV-1. Potential Effects of Some Sources of Alteration on Water Quality Parameters; D = Decrease, I = Increase, C = Change threat to aquatic life than to do nothing. Under the do nothing alternative, the toxics may remain in the sediment in a biologically-unavailable form, whereas dredging might resuspend the toxic fraction, making it biologically available and also facilitating wider distribution in the water body.

The points touched upon above are presented to suggest some of the phenomena which may be of importance in a water body survey, and to suggest the need to recognize whether or not they may realistically be manipulated. Those which cannot be manipulated essentially define the limits of the highest potential use that might be realized in the water body. Those that can be manipulated define the levels of improvement that are attainable, ranging from the current aquatic life uses to those that are possible within the limitations imposed by factors that cannot be manipulated.

RESTORATION OF USES

Uses that have been impaired or lost in an estuary can only be restored if the conditions responsible for the impairment are corrected. Impairment can be attributed to pollution from toxics or overenrichment with nutrients. Uses may also be lost through such activities as the disposal of dredge and fill materials which smother plant and animal communities, through overfishing which may deplete natural populations, the destruction of freshwater spawning habitat which will cause the demise of anadromous species, and natural events in the sea, such as the shifting of ocean currents, that may alter the migration routes of species which visit the estuary at some time during the life cycle. One might expect losses due to natural phenomena to be temporary although man-made alterations of the estuarine environment may prevent restoration through natural processes.

Assuming that the factors responsible for the loss of species have been identified and corrected, efforts may be directed towards the restoration of habitat followed by natural repopulation, stocking of species if habitat has not been harmed, or both. Many techniques for the improvement of substrate composition in streams have been developed which might find application in estuaries as well. Further discussion on the importance of substrate composition will be found in the Technical Support Manual (EPA, November 1983).

Stocking with fish in freshwater environments, and with young lobster in northeastern marine environments, is commonly practiced and might provide models for restocking in estuaries. In addition, aquaculture practices are continually being refined and the literature on this subject (Bardach et al., 1972) should prove helpful in developing plans for the restoration of estuaries or parts of estuaries.

Submerged aquatic vegetation (SAV) is considered to be an excellent indicator of the overall health of an estuary because it is sensitive to environmental degradation caused by physical smothering, nutrient enrichment and toxics. Because SAV is so important as habitat and as a source of nutrient for a wide range of the estuarine biota, its demise signals the demise of its dependent populations. If uses in an estuary have been impaired or lost, it is likely that SAV will also have been affected.

Unfortunately, the cause of SAV degradation is not always clear. In the Chesapeake Bay for instance, controversy persists as to the cause of loss of SAV and the loss of biota which depend to whatever extent on SAV. Trends noted over time in the demise of these populations may conceivably be related to trends in toxic, sediment and nutrient loadings on the Bay, and to trends in the release of chlorinated wastewaters from POTWs, chlorinated effluents from industry and chlorinated cooling water from powerplants. Areas in which SAV has been adversely impacted are areas where there are toxics in the sediment and/or where algal blooms prevent light from reaching SAV communities.

The ability to restore areas of SAV will depend upon the initial causes of loss, and the ability to remove the causes. Toxics in sediment may be a particularly difficult problem because of the impracticality of dredging large areas to remove contaminated bottom substrate. An inabilty to remove toxic sediments which may have caused a decline in SAV and other benthic communities severely limits the likelihood that these populations may be restored to past levels.

The control of nutrients may be a much more tractable problem. If nutrient inputs to the estuary can be controlled, SAV populations may begin to expand on their own. In the Potomac River estuary, phosphorus removal at the Blue Plains wastewater treatment plant, which serves the greater Washington, D.C. area, has resulted in sharp reductions in algal blooms which are considered a major factor in the demise of SAV within the Chesapeake Bay system.

Apart from natural processes which result in the enlargement of areas of SAV, SAV may be restored through reseeding and transplanting, depending upon the species. Generally speaking, reseeding may not be a practical approach because of the cost of collecting seeds and because one would not expect all seeds to survive, although Vallisneria (wild celery) shows some promise in using seeds to reestablish populations. Some areas may reseed naturally, but in many cases SAV populations may be too distant for the natural transport of seeds to be likely. In these cases, plants may be transplanted in order to restore SAV. Reestablishment is accomplished by transplanting shoots and rhizomes.

Although transplanting may be a more practical alternative, the outcome is not assured. In an effort to reestablish SAV, plugs of Zostera (eelgrass) and Potamogeton (sage pondweed, redhead grass) were planted in the Potomac River estuary. These beds showed some measure of success, depending mainly upon the substrate present. The transplanting of SAV is a labor intensive operation and as such would require a considerable cost in time and resources to restore even a small area.

In Tampa Bay, Florida, stress on the ecosystem, including the disposal of dredge spoils which have smothered SAV communities, has caused a significant loss (25,220 ha, or 81 percent) of submergent wetland vegetation. Efforts to reestablish Spartina (cord grass) and Thalassia (turtlegrass) have resulted in the restoration of about 11 ha of vegetation (the growth and spreading of rhizomateous material is increasing this figure) (Hoffman et al., 1982). The transplantation of Thalassia and Halodule (shoalgrass) near the discharge side of a powerplant was less successful, in that

Thalassia failed to survive for 30 days where the mean water temperature was 31°C or greater, and only small patches of shoalgrass survived near the outer edges of the thermal plume. These differences could not be attributed to differences in sediment composition (Blake et al., 1976). Nevertheless, other transplantation efforts emphasize the importance of substrate to plant survival. For example, Thalassia prefers a reduced environment while Halodule prefers an oxidized substrate.

Transplanting oyster spat from "seed" areas which are protected from harvesting to areas less favorable for reproduction is a relatively common practice. Seed areas ideally exhibit optimum salinity and temperature for oyster reproduction and spat set. Clean shell is deposited as substrate in seed areas and spat often become very densely populated. Spat are then moved to areas where an oyster population is desired. Steps may also be taken to prepare the bottom (often by depositing oyster shells) where an oyster reef exists, or where attempts will be made to establish an oyster reef.

Although there has been some progress in the aquacultural sciences towards rearing species that may be found in the estuary (clam, quahog, oyster, scallop, shrimp, crab, lobster, flatfish), techniques are not well-advanced and there is little likelihood that they could be successfully applied on any scale towards the repopulation of the estuary. As with SAV, the experiments and the successes with the reestablishment of speties are limited, and the more important factor in the restoration of habitat is the control and reversal of the various forms of pollution which catse the demise of estuarine populations.

CHAPTER V

REFERENCES

Addy, C.E. and D.A. Aylward. Status of eelgrass in Massachusetts during 1943. J. Wildl. Mgr. 8:265-275, 1944.

Adkins, G. and P. Bowman. A study of the fauna in dredged canals of coastal Louisiana. La. Wildl. Fish Comm. Tech. Bull., 18:1-72, 1976.

Adkins, G., J. Tarver, P. Bowman, and B. Savoie. A study of the commerical finfish in coastal Louisiana. La. Dep. Wildl. Fish., Seafood Div. Tech. Bull., 29:1-87, 1979.

Ahlstrom, E.H., et al. Sampling zooplankton to determine biomass. In: Recommended procedures for measuring the productivity of plankton standing stock and related oceanic properties, E.H. Ahlstrom (ed.), Washington, D.C., National Academy of Sciences, 1969.

Alheit, J. and W. Schneibel. Benthic harpacticoids as a food source for fish. Marine Biology 70:141-147, 1982.

Allen, L.G. and M.H. Horn. Abundance, Diversity and Seasonality of Fishes in Colorado Lagoon, Alamitos Bay, California. Estuarine and Coastal Marine Sci. 3:371-380, 1975.

Ambrose, R.B., T.O. Najarian, G. Bourne, and M.L. Thatcher. Models for Analyzing Eutrophication in Chesapeake Bay Watersheds: A Selection Methodology. EPA, Chesapeake Bay Program, Annapolis, MD, 1981.

American Public Health Association. National Shellfish Sanitation Program Manual of Operations: Part 1, Sanitation of Shellfish Growing Areas. 1965.

Anderson, R.R. Ecology and Mineral Nutrition of _Myriophyllum spicatum_ (L.). M.S. Thesis, Univ. Maryland, College Park, 1964.

Anderson, R.R. Submerged vascular plants of the Chesapeake Bay and tributaries. Chesapeake Sci. 13(suppl.):S87-S89, 1972.

Anderson, R.R. Temperature and rooted aquatic plants. Chesapeake Sci. 10(3 and 4):157-164, 1969.

Anderson, R.R., R.G. Brown, and R.D. Rappleye. Mineral composition of Eurasian watermilfoil, _Myriophyllum spicatum._ Chesapeake Sci. 6(1):68-72, 1965.

Anonymous. Creeping and crawling on Currituck Sound, the dilemma of Eurasian watermilfoil. Univ. North Carolina Sea Grant News Letter, 1976.

Arasaki, M. The ecology of Amamo (_Zostera marina_) and Koamamo (_Zostera nana_). Bull. Jap. Soc. Sci. Fish. 15:567-572, 1950a.

Arasaki, M. Studies on the ecology of Zostera marina and Zostera nana. 11. Bull. Jap. Soc. Fish. 16:70-76, 1950b.

Arnold, C.R., T.D. Williams, W.A. Fable, Jr., J.L. Lasswell, and W.H. Bailey. Methods and Techniques for Spawning and Rearing Spotted Seatrout in the Laboratory. Proc. Annu. Conf. Southeast. Assoc. Game Fish Comm. 30:167-178, 1978.

Auld, A.H. and J.R. Schubel. Effects of Suspended Sediment on Fish Eggs and Larvae: A Laboratory Assessment. Estuarine Coastal Mar. Sci. 6:153-164, 1978.

Backman, T.W. and D.C. Barilotti. Irradiance reduction: effects on standing crops of the eelgrass Zostera marina in a coastal lagoon. Mar. Biol. 34:33-40, 1976.

Bain, M.B. and J.L. Bain. Habitat Suitability Index Models: Coastal Stocks of Striped Bass. U.S. Dept. Int. Fish Wildl. Serv., Washington, D.C. FWS/OBS-82/10.1, 1982.

Baker, F.C. The productivity of invertebrate fish food on the bottom of Oneida Lake, with special reference to mollusks. New York State College of Forestry, Syracuse Univ. Tech. Pub. No. 9 18(2), 1918.

Bardach, J.E., J.H. Ryther, and W.O. McLarney. Aquaculture - The Farming and Husbandry of Freshwater and Marine Organisms. Wiley-Interscience, New York, 1972.

Barger, L.E., L.A. Collins, and J.H. Finucane. First record of bluefish larvae, Pomatomus saltatrix, in the Gulf of Mexico. Northeast Gulf Sci. 2(2):145-147, 1978.

Beal, E.O. A manual of marsh and aquatic vascular plants of North Carolina with habitat data. Tech. Bull. of the North Carolina Agric. Exp. Sta. 247, 1977.

Beauchamp, D.A., M.F. Shepard, and G.B. Pauley. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest)--chinook salmon. U.S. Fish and Wildl. Serv. FWS/OBS-82/11.6, 1983.

Beaven, M. and J. Mihursky. Food and Feeding Habits of Larval Striped Bass: An Analysis of Larval Striped Bass Stomachs from 1976 Potomac Estuary Collections. Prepared by Chesapeake Biological Laboratory for md. Power Plant Siting Program, Dept. Natural Res., Annapolis, Md. UMCEES Ref. No. 79-45-CBL, 1980.

Beccasio, A.D., G.H. Weissberg, A.E. Redfield, et al. Atlantic Coast Ecological Inventory: User's Guide and Information Base. Washington, D.C., Biological Services Program, U.S. Fish and Wildlife Service, 1980.

Beccasio, A.D., J.S. Isakson, A.E. Redfield, et al. Pacific Coast Ecological Inventory: User's Guide and Information Base. Washington, D.C., U.S. Fish and Wildl. Serv., FWS/OBS-81/30, 1981.

Beccasio, A.D., N. Fotheringham, A.E. Redfield, R.L. Frew, W.M. Levitan, J.E. Smith, and J.O. Woodrow, Jr. Gulf Coast Ecological Inventory: User's Guide and Information Base. Washington, D.C., U.S. Fish and Wildl. Serv., Biol. Serv. Program, FWS/OBS-82/55, 1982.

Benson, N.G. (ed.). Life History Requirements of Selected Finfish and Shellfish in Mississippi Sound and adjacent areas. U.S. Fish and Wildl. Serv., Office of Biological Services, Washington, D.C., FWS/OBS-81/51, 1982.

Biebel, R. and C.P. McRoy. Plasmitic resistance and rate of respiration and photosynthesis of Zostera marina at different salinities and temperatures. Mar. Biol. 8:48-56, 1971.

Binford, M.W. Crustacean zooplankton ecology of the Atchafalaya River Basin, Louisiana. M.S. Thesis, LSU, Baton Rouge, LA, 1975.

Blake, N.J., L.J. Doyle, and T.E. Pyle. The Macrobenthic community of a thermally altered area of Tampa Bay, Florida. In: Thermal Ecology II, F.W. Esch and R.W. McFarlone, eds., Technical Information Center, Energy Research and Development Administration, 1976. pp. 296-301.

Blumberg, A.F. A Numerical Investigation into the Dynamics of Estuarine Circulation. Chesapeake Bay Institute of the Johns Hopkins University, TR91, October 1975.

Bourn, W.S. Ecological and physiological studies on certain aquatic angiosperms. Cont. Boyce Thompson Inst. 4:425-496, 1932.

Bourn, W.S. Sea-water tolerance of Vallisneria spiralis L. and Potamogeton foliosus. Cont. Boyce Thompson Inst. 6:303-308, 1934.

Boyer, J.S. Studies of the physiology, ecology and structure of Myriophyllum spicatum L. Univ. of Maryland. CBL Ref. No. 60-63, 1960.

Boynton, W.R., W.M. Kemp, and C.W. Keefe. A comparative analysis of nutrient and other factors influencing estuarine phytoplankton production. In: V.S. Kennedy (ed.), Estuarine Comparisons, Academic Press, New York, NY, 1982.

Boynton, W.R., T.T. Polgar, and H.H. Zion. Importance of Juvenile Striped Bass Food Habits in the Potomac Estuary. Trans. Am. Fish. Soc. 110:56-63, 1981.

Brice, L.P. Zooplankton community structure: The effects of long-term petroleum operations in Southeastern Louisiana salt marshes. M.S. Thesis, Louisiana State University, Baton Rouge, LA, 1983.

Burbidge, R.G. Distribution, Growth, Selective Feeding, and Energy Transformations of Young-of-the-Year Blueback Herring, Alosa aestivalis (Mitchill), in the James River, Virginia. Trans. Am. Fish. Soc. 2:297-311, 1974.

Cake, E.W., Jr. Habitat Suitability Index Models: Gulf of Mexico American Oyster. U.S. Dept. Int. Fish Wildl. Serv., FWS/OBS-82/10.57, 1983.

Cameron, W.M. and D.W. Pritchard. Estuaries. In: The Sea, M.N. Hill, ed., John Wiley and Sons, NY, 2:306-324, 1963.

Camp Dresser & McKee, Inc. Procedure for Establishing Water Quality Goals for Tampa Bay Wasteload Allocation Study. Prepared for Florida Dept. of Environmental Regulation, September 1983.

Camp Dresser & McKee, Inc. Wastewater Reclamation Facilities and Effluent Disposal Plan: City of Naples, Florida. Prepared for City of Naples, FL, June 1983.

Carriker, M.R. Ecology of Estuarine Benthic Invertebrates: A Perspective. In: Estuaries, G.H. Lauff, ed., American Association for the Advancement of Science, Washington, D.C., 1967. pp. 442-487.

Castagna, M. and P. Chanley. Salinity Tolerance of Some Marine Bivalves from Inshore and Estuarine Environments in Virginia Waters on the Western Mid-Atlantic Coast. Malacologia, 12:47-96, 1973.

Chabreck, R.H. and R.E. Condrey. Common vascular plants of the Louisiana marsh. LSU-CWR. Sea Grant Pub. No. LSU-T-79-003, 1979.

Chao, L.N. and J.A. Musick. Life History, Feeding Habits, and Functional Morphology of Juvenile Sciaenid Fishes in the York River Estuary, Virginia. Fish. Bull. 75:657-702, 1977.

Chapman, V.J., J.M.A. Brown, C.F. Hill, and J.L. Carr. Biology of excessive weed growth in the hydro-electric lakes of the Waikato River, New Zealand. Hydrobiologia 44:349-363, 1974.

Cheng, R. Unreferenced in Zison et al., 1977.

Chen, H.S. Hydrodynamic and Biogeochemical Water Quality Models of Hampton Roads. SR No. 147, Virginia Institute of Marine Science, Gloucester Point, VA, February 1978.

Christmas, J.Y. and R.S. Waller. Estuarine vertebrates, Mississippi. Pages 320-434 in J.Y. Christmas, ed. Cooperative Gulf of Mexico estuarine inventory and study, Mississippi. Gulf Coast Research Laboratory, Ocean Springs, MS, 1973.

Christmas, J.Y., J.T. McBee, R.S. Waller, F.C. Sutter III. Habitat Suitability Index Models: Gulf Menhaden. U.S. Dept. Int. Fish Wildl. Serv., Washington, D.C. FWS/OBS-82/10.23, 1982.

Chrysler, F.S., F.H. Blodgett, and F.W. Besley. The plant life of Maryland. Johns Hopkins Press, Baltimore, MD, 1910.

Colebrook, J.M. The design of sampling surveys. FAO. Fish. Tech. Pap., (122):52-8, 1983.

Cook, C.D.K., B.J. Gut, E.M. Rix, J. Schneller, and M. Geitz. Water plants of the world, a manual for the identification of the genera of freshwater macrophytes. Dr. W. Junk b.v., Publishers, The Hague, Netherlands, 1974.

Correl, D.S. and H.B. Correll. Aquatic and wetland plants of the southwestern United States. Stanford Univ. Press, Stanford, 1972.

Correll, D.L., T. Wu, J.W. Pierce, and M.A. Faust. Rural non-point pollution studies in Maryland (Non-point pollution studies on agricultural land use types prevalent in the Coastal Plain zone of Maryland). EPA 904/9-77-001. Washington, D.C., 1977.

Cottam, C. and D.A. Munro. Eelgrass status and environmental relations. J. Wildl. Mgt. 18:449-460, 1954.

Cottam, C. The eelgrass shortage in relation to waterfowl. Trans. Amer. Game Conf. 20:272-279, 1934.

Couch, J.A. Shrimps (Arthropoda: Crustacea: Penaeidae). In: Pollution Ecology of Estuarine Invertebrates. C.W. Hart, Jr. and S.L.H. Fuller, eds. Academic Press, New York, 1979. pp. 236-257.

Coull, B.C., G.R. Hicks, and J.B.J. Wells. Nematode/copepod ratios for monitoring pollution: A rebuttal. Mar. Pollut. Bull., 12:381-383, 1981.

Cuzon du Rest, R.P. Distribution of the zooplankton in the salt marshes of southeastern Louisiana. Publ. Inst. Mar. Sci., Univ. Tex. 9:132-155, 1963.

Daiber, F.C., L.L. Thornton, K.A. Bolster, T.G. Campbell, O.W. Crichton, G.L. Esposito, D.R. Jones, J.M. Tyrawski. An Atlas of Delaware's Wetlands and Estuarine Resources, Technical Report Number 2. College of Marine Studies, University of Delaware, Newark, Delaware, 1976.

Davis, H.C. and A. Calabrese. Combined Effects of Temperature and Salinity on Development of Eggs and Growth of Larvae of M. mercenaria and C. virginica. USFWS Fishery Bull. 63:643-655, 1964.

Dawson, E.Y. Marine botany. Holt, Rinehart and Winston, Inc., New York, 1966.

Deane, W. Zannichellia palustris, an additional record. Phodora 12:12, 1910.

DeFalco, P. The Estuary-Septic Tank of the Megalopolis. In: Estuaries, Lauff, G.H. ed., Am. Assoc. for the Advancement of Science, 83:701-707, 1967.

Devlin, R.M. Influence of phenoxy growth regulators on the uptake of naptalam by Potamogeton pectinatus. Proc. Northeast Weed Sci. Soc. 27:115-119, 1973.

Diaz, R.J. Habitat Suitability Index Models: Juvenile Atlantic Croaker. U.S. Dept. Int. Fish Wildl. Serv., Washington, D.C. FWS/OBS-82/10.21, 1982.

Dillon, C.R. A comparative study of the primary productivity of estuarine phytoplankton and macrobenthic plants. Ph.D. Thesis, Univ. North Carolina, Chapel Hill, 1971.

DiToro, D.M., J.J. Fitzpatrick, and R.V. Thomann. Water Quality Analysis Simulation Program (WASP) and Model Verification Program (MVP) - Documentation. Prepared for EPA, Duluth, MN, by Hydroscience, Inc., Westwood, NJ, 1981.

Domermuth, R.B. and R.J. Reed. Food of Juvenile American Shad, Alosa sapidissima, Juvenile Blueback Herring, Alosa aestivalis, and Pumpkinseed, Lepomis gibbosus, in the Connecticut River Below Holyoke Dam, Massachusetts. Estuaries. 3:65-68, 1980.

Doroshev, S.I. Biological Features of the Eggs, Larvae, and Young of the Striped Bass, Roccus saxatilis (Walbaum), in Connection with the Problem of Its Acclimatization in the U.S.S.R. J. Ichthyol. 10:235-248, 1970.

Down, Cherie. Use of aerial imagery in determining submerged features in three east-coast Florida lagoons. Florida Scientist, 46:355-362, 1983.

Drummond, N.A. Macrozooplankton of Lake Pontchartrain Louisiana. M.S. Thesis, LSU, Baton Rouge, LA, 1982.

Drummond, S.B. and G. Pellegrin, Jr. The abundance and distribution of sea catfish (Arius felis) in the Gulf of Mexico. Proceedings 2nd Annual Tropical and Subtropical Fisheries Technical Conference of the Americas. Texas A&M Univ., Sea Grant Publ. TAMU-SG-78-107, 1977.

Durbin, A.G. and E.G. Durbin. Grazing Rates of the Atlantic Menhaden Brevoortia tyrannus as a Function of Particle Size and Concentration. Marine Biol. 33:265-277, 1975.

Dyer. Estuaries: A Physical Introduction. John Wiley and Sons, NY, 1973.

Dynamic Estuary Model Documentation, prepared by WRE, Inc. and CH2M Hill for the Berkely, Charleston, and Dochester Counties, S.C., Council of Governments. 208 Areawide Wastewater Management Plan. December 1977.

Elliott, A.J. A Numerical Model of the Internal Circulation in a Branching Tidal Estuary. Chesapeake Bay Institute of the Johns Hopkins University, SR54, June 1976.

Ellis, M.M., B.A. Westfall, D.K. Meyer, and W.S. Platner. Water Quality Studies of the Delaware River with Reference to Shad Migration. USFWS Spec. Sci. Rep. No. 38, 1947.

Emery, K.O. and R.E. Stevenson. Estuaries and Lagoons. I. Physical and Chemical Characteristics. In: Treatise on Marine Ecology and Paleoecology I., J.W. Hedgpeth ed., Geol. Soc. Am., 67:673-693, 1957.

Erkenbrecher, C.W. Sediment bacteria as a water quality indicator in the Llynnhaven Estuary. Bull. 126, Virginia Water Resources Research Center, Blacksburg, VA, 1980.

Etchevers, S.L. Contribution to the biology of the sea catfish, Arius spixii (Agassiz) (Pisces - Ariidae), south of Margarita Island, Venezuela. Bull. Mar. Sci. 28(2):381-285, 1978.

Etzold, D.J. and J.Y. Christmas (eds.). A Mississippi marine finfish management plan. A report by the Mississippi-Alabama Sea Grant Consortium. MASGP-78-146, 1979.

Fable, W.A., Jr., T.D. Williams, and C.R. Arnold. Description of Reared Eggs and Young Larvae of the Spotted Seatrout Cynoscion nebulosis. Fish. Bull. 76:65-71, 1978.

Fassett, N.C. A manual of aquatic plants. Univ. Wisconsin Press, Madison, 1960.

Federle, T.W. and D.C. White. Preservation of estuarine sediments for lipid analysis of biomass and community structure of microbiota. Appl. Environ. Microbiol., 44:1166-1169, 1982.

Felfoldy, L.J.M. Apparent photosynthesis of Potamogeton perfoliatus L. in different depths of Lake Balaton. Annals. Inst. Biol. Tihany 27:201-208, 1960.

Ferris, V.R. and J.M. Ferris. Thread Worms (Nematoda). In: Pollution Ecology of Estuarine Invertebrates, C.W. Hart, Jr. and S.L.H. Fuller, eds. Academic Press, New York, 1979. pp. 1-33.

Fischer, H.B. Mass Transport Mechanisms in Partially Stratified Estuaries. Journal of Fluid Mechanics, 53:672-687, 1972.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, and N.H. Brooks. Mixing in Inlands and Coastal Waters. Academic Press, NY, 1979.

Florschutz, O., Jr. The importance of Eurasian watermilfoil (Myriophyllum spicatum) as a waterfowl food. Proc. Southeastern Assoc. Game Fish Comm. Conf. 26:189-194, 1973.

Galtsoff, P.S. The American Oyster, Crassostrea virginica, Gmelin. U.S. Fish & Wildlife Ser. Bull. No. 64, 1964.

Genet, L.A., D.J. Smith, and M.B. Sonnen. Computer Program Documentation for the Dynamic Estuary Model. Prepared for Systems Development Branch, EPA, Washington, D.C., by Water Resources Engineers, Inc., Walnut Creek, CA, 1974.

Gillespie, M.C. Analysis and treatment of zooplankton of estuarine waters of Louisiana. In: Perret W.S. et al. (eds.), Cooperative Gulf of Mexico estuarine inventory and study, Louisiana. Phase IV: Biology, Section II. Louisiana Wildlife and Fisheries Commission. 1971.

Gray, J.S. and F.B. Mirza. A possible method for the detection of pollution-induced disturbance on marine benthic communities. Mar. Poll. Bull., 10:142-146, 1979.

Green, J. The Biology of Estuarine Animals. University of Washington, Seattle, 1968.

Gunter, G. Studies on marine fishes of Texas. Publ. Inst. Mar. Sci., Univ. of Texas. 1(1):1-190, 1945.

Gunter, G. Observations on breeding of the marine catfish, Galeichthys felis (Linnaeus). Copeia (4):217-223, 1947.

Gunter, G. A revised list of euryhaline fishes of North and Middle America. Am. Midl. Nat. 56(2):345-354, 1956.

Gutsell, J.S. Natural history of the bay scallop. U.S. Bur. Fish. Bull. 46:569-632, 1930.

Haedrich, R.L. Estuarine Fishes. In: Ecosystems of the World: Estuaries and Enclosed Seas, B.H. Ketchum, ed. Elsevier Scientific Publishing Company, New York, 1983. pp. 183-207.

Hamilton, P. A Numerical Model of the Vertical Circulation of Tidal Estuaries and its Application to the Rotterdam Waterway. Geophysics Journal of the Royal Astr. Society, 40:1-21, 1975.

Hansen, D.V. and M. Rattray. Gravitational Circulation in Estuaries. Journal of Marine Research, 23:104-122, 1965.

Hansen, D.V. and M. Rattray. New Dimension in Estuary Classification. Limnology and Oceanography, 11:319-326, 1966.

Hardy, J.D. Development of fishes of the mid-Atlantic bight, at atlas of egg, larval and juvenile stages. U.S. Fish and Wildl. Serv., Biol. Serv. Program FWS/OBS-78/12, Vol. III, 1978.

Harleman, D.R.F. Hydrodynamic Model - One Dimensional Models. In: Estuarine Modeling: An Assessment, Ch. II-3. EPA Water Pollution Control Research Series, NO. 16070 DZV 02/71, 1971, pp 34-90.

Harleman, D.R.F. The Significance of Longitudinal Dispersion in the Analysis of Pollution in Estuaries. Proceedings and International Conference on Water Pollution Research, Tokyo, Pergamon Press, New York, 1984.

Harvey, E.J. Observation on the distribution of the sea catfish Arius felis larvae with and without chorion with respect to salinity in the Biloxi Bay, Mississippi Sound area. J. Miss. Acad. Sci., 17:77, 1971.

Haven, D.S. and R. Morales-Alamo. Filtration of Particles from Suspension by the American Oyster, Crassostrea virginica. Biol. Bull. 139:248-264, 1970.

Haven, D.S. Distribution, Growth, and Availability of Juvenile Croaker, Micropogon undulatus, in Virginia. Ecology. 38:88-97, 1957.

Haven, D.S. The Shellfish Fisheries of the Potomac. In: The Potomac Estuary, biological resources, trends and options. W.T. Mason and K.C. Flynn, eds. Interstate Commission on the Potomac River Basin, 1978. pp. 88-94.

Heard, R.W. Guide to Common Tidal Marsh Invertebrates of the Northeastern Gulf of Mexico. Mississippi-Alabama Sea Grant Consortium, 1982.

Hildebrand, S.F. and W.C. Schroeder. Fishes of Chesapeake Bay. Bull. U.S. Bur. Fish. 43:244-247, 1928.

Hocutt, C.H. Fish. In: WPCF Pre-Conference Workshop: Use Attainability Analysis. Atlanta, Georgia, 1983.

Hodgson, R.H. and N.E. Otto. Pondweed growth and response to herbicides under controlled light and temperature. Weeds 11:232-237, 1963.

Hoffman, W.E., M.J. Durako, and R.R. Lewis, III. Habitat restoration in Tampa Bay, Florida. Bay Area Scientific Information Symposium, May 1982.

Hoff, J.G. and R.M. Ibara. Factors Affecting the Seasonal Abundance, Composition and Diversity of Fishes in a Southeastern New England Estuary. Estuarine and Coastal Marine Sci., 5:665-678, 1977.

Hollis, E.H. Variations in the Feeding Habits of the Striped Bass Roccus saxatilis (Walbaum), in Chesapeake Bay. Bull. Bingham. Oceanog. Coll. 14:111-131, 1952.

Holme, N.A. and A.D. McIntyre (eds). Methods for study of Marine Benthos. International Biological Program Handbook No. 16. Blackwell Scientific Publ., Oxford, 1971.

Hotchkiss, N. Underwater and floating-leaved plants of the United States and Canada. Bureau Sport Fish. Wildl. No. 44. Washington, D.C., 1967.

Hudson, L.L. and J.D. Hardy, Jr. Summary of the Biology of White Perch. In: Water Quality Criteria and the Biota of Chesapeake Bay. Prepared by the Chesapeake Research Consortium, Inc. for U.S. Army Corps. Eng., Baltimore District, Baltimore, MD. CRC Publ. No. 41. pp. 2-97, 1974.

Hulings, N.C. and J.S. Gray (eds.). A manual for the study of meiofauna. Smithsonian Contri. Zool. No. 78, 1971.

Hutchinson, G.E. A treatise of limnology, limnological botany. Vol. III. John Wiley and Sons, New York, 1975.

Idyll, C.P. and W.E. Fahy. Spotted Seatrout ... Shallow-Water Sport Fish. Marine Resources of the Atlantic Coast. Leaflet Number 13. Atlantic States Marine Fisheries Commission. Washington, D.C., 1975.

Ingle, R.M. Spawning and Setting of Oysters in Relation to Seasonal Environmental Changes. Bulletin of Marine Science of the Gulf and Caribbean, 1:111-135, 1951.

Jeffries, H.P., K. Sherman, R. Maurer, and C. Katsinis. Computer-processing of zooplankton samples. In: V.S. Kennedy (ed.), Estuarine Perspectives. Academic Press, New York, NY, 1980.

Joanen, T. and L.L. Glasgow. Factors influencing the establishment of widgeongrass stands in Louisiana. Southeastern Assoc. Game Fish Comm. Conf. 19:78-92, 1965.

Johnson, G.D. Development of fishes in the mid-Atlantic bight, an atlas of egg, larval, and juvenile stages. U.S. Fish and Wildl. Serv., Biol. Serv. Program, FWS/OBS-78/12, Vol. IV, 1978.

Jones & Stokes Associates, Inc. Ecological Characterization of the Central and Northern California Coastal Region. U.S. Fish and Wildlife Services. FWS/OBS-80/46.2, 1981.

Jones, P.W., F.D. Martin, and J.D. Hardy, Jr. Development of Fishes of the Mid-Atlantic Bight. An Atlas of Egg, Larval and Juvenile Stages. Volume I. Acipenseridae through Ictaluridae. U.S. Department of the Interior, Fish and Wildlife Service, Biological Services Program. FWS/OBS-78/12, 1978.

deJonge, V.N. and L.A. Bouwman. A simple density separation technique for quantitative isolation of meiobenthos using the colloidal silica ludox-TM. Marine Biology, 42:143-148, 1977.

Josai, J.W. Annotated bibliography of zooplankton sampling devices. NOAA Tech. Rep. NMFS/SSRF, (609):90 pp., 1970.

Joseph, E.B. The Status of the Sciaenid Stocks of the Middle Atlantic Coast. Ches. Sci. 13:87-100, 1972.

June, F.C. and F.T. Carlson. Food of Young Atlantic Menhaden, Brevoortia tyrannus, in Relation to Metamorphosis. Fish. Bull. 68:493-512, 1971.

Kadlec, J.H. and W.A. Wentz. State of the art survey and evaluation of marsh plant establishment techniques: Induced and natural, Vol. I, TR D-74-9, U.S. Army Engineer Waterways Experiment Station. Vicksburg, MS, 1974.

Kawamura, T. Distribution of Phytoplankton Populations in Sandy Hook Bay and adjacent areas in relation to Hydrographic Conditions in June, 1962. Tech. Pap. Bureau Sport Fish. Wildl. Wash., 1:1-37, 1966.

Kendall, A.W., Jr. and F.J. Schwartz. Lethal Temperature and Salinity Tolerances for White Catfish, Ictalurus catus, from the Patuxent River, Maryland. Ches. Sci. 9:103-108, 1968.

Kerwin, J.A., R.E. Munro, and W.W. Peterson. Distribution and abundance of aquatic vegetation in the upper Chesapeake Bay 1971-1974. U.S. Fish Wildl. Serv. Patuxent Wildl. Research Sta. Mimeo., 1975.

Ketchum, B.H. The Exchanges of Fresh and Salt Water in Tidal Estuaries. Journal of Marine Research, 10:18-38, 1951.

Kilby, J.D. The fishes of two Gulf coastal marsh areas of Florida. Tulane Stud. Zool. 2(8):175-247, 1955.

Korringa, P. Recent Advances in Oyster Biology. The Quart. Rev. of Biol. 27:266-365, 1952.

Lee, D.S., C.R. Gilbert, C.H. Hocutt, R.E. Jenkins, D.E. McAllister, and J.R. Stauffler. Atlas of North American freshwater fishes. North Carolina State Museum of Natural History. Biol. Serv. Publ. No. 1980-12, 1980.

Lee, G. Oral gestation in the marine catfish, Galeichthys felis. Copeia (1):49-56, 1937.

Leendertse, J.J., R.C. Alexander, and S.K. Liu. A Three-Dimensional Model for Estuaries and Coastal Seas: Volume 1, Principles of Computation. R-1417-OWRT, The Rand Corporation, Santa Monica, CA, December 1973.

Leimkuhler, W. A Two-Dimensional Finite-Element Dispersion Model. M.S. Thesis, M.I.T., August 1974.

Lippson, A.J., ed. The Chesapeake Bay in Maryland: An Atlas of Natural Resources. The Johns Hopkins Univ. Press, Baltimore, MD, 1973.

Lippson, A.J., M.S. Haire, A.F. Holland, F. Jacobs, J. Jensen, R.L. Moran-Johnson, T.T. Polgar, and W.A. Richkus. Environmental Atlas of the Potomac Estuary. Prepared by Martin Marietta Corp. for MD. Power Plant Siting Program, Dept. Natural Res., Annapolis, MD, 1979.

Lippson, R.L. Blue Crab Study in Chesapeake Bay Maryland: Ann. Progress Rept. Univ. of Maryland Natural Resources Institute, Chesapeake Biological Lab., Solomons, MD. Ref. No. 71-9, 1971.

Loos, J. Shore and Tributary Distribution of Ichthyoplankton and Juvenile Fish with a Study of Their Food Habits. Prepared by Acad. of Natural Sciences of Philadelphia, PA. for MD. Power Plant Siting Program, Dept. Natural Res., Annapolis, MD (cited in Lippson et al. 1979), 1975.

Lorio, Wendell J. and William S. Perret. Biology and Ecology of the Spotted Seatrout (Cynoscion Nebulosus Cuvier). In: Proceedings of the Red Drum and Seatrout Colloquium, October 19-20, 1978. pp. 7-13, 1980.

Lucy, J.A. The Reproductive Cycle of Mya arenaria L. and Distribution of Juvenile Clams in the Upper Portions of the Nearshore Zone of the York River, Virginia. M.S. Thesis, The College of William and Mary, Williamsburg, VA, 1977.

Mansueti, A.J. and J.D. Hardy, Jr. Development of Fishes of the Chesapeake Bay Region. Port City Press, Baltimore, MD, 1967.

Mansueti, A.J. Movements, Reproduction, and Mortality of the White Perch, Roccus americanus, in the Patuxent Estuary, Maryland. Ches. Sci. 2:142-205, 1961.

Martin, A.C. and F.M. Uhler. Food of game ducks in the United States and Canada. U.S. Dept. Agr. Tech. Bull. 634. Washington, D.C., 1939.

Martin, A.C., H.S. Zim, and A.L. Nelson. American wildlife and plants, a guide to wildlife food habits. Dover Publ., Inc., New York, 1951.

Mason, H.L. A flora of the Marshes of California. Univ. California Press, 1969.

McErlean, A.J., S.G. O'Connor, J.A. Mihursky and C.I. Gibson. Abundance, Diversity and Seasonal Patterns of Estuarine Fish Populations. Estuarine and Coastal Marine Sci., 1:19-36, 1973.

McHugh, J.L. and J.C. Ginter. Fisheries. MESA New York Bight Atlas Monograph 16, 1978.

McHugh, J.L. Estuarine Nekton. In: Estuaries, G.H. Lauff, ed. American Association for the Advancement of Science, Washington, D.C., 1967.

McIntyre, A.D. and D.J. Murison. The meiofauna of a flatfish nursery ground. Journal of the Marine Biological Association of the United Kingdom, 53:93-113, 1973.

McLusky, D.S. Ecology of Estuaries. Heinemann Educational Books, Ltd. London, 1971.

McLusky, D.S. The Estuarine Ecosystem. John Wiley and Sons, New York, 1981.

McMillan, C. Salt tolerance of mangroves and submerged aquatic plants, pp. 379-390. In R.J. Reimold and W.H. Queen, eds., Ecology of halophytes, Academic Press, New York, 1974.

McRoy, C.P. The distribution and biogeography of Zostera marina (eelgrass) in Alaska. Pacific Sci. 22:507-513, 1968.

Md. Dept. Nat. Res. Interstate Fisheries Management Plan for the Striped Bass of the Atlantic Coast from Marine to North Carolina. Contract to the Atlantic States Marine Fisheries Comm. Cooperative Agreement No. NA-8-FA-00017. Nat. Mar. Fish. Serv., Gloucester, MA, 1981.

Menzel, W. Clams and Snails [Mollusca: Pelecypoda (except oysters) and Gastropoda]. C.W. Hart, Jr. and S.L.H. Fuller, eds. Academic Press, New York, 1979. pp. 371-396.

Merrill, A.S. and H.S. Tubiash. Molluscan Resources of the Atlantic and Gulf Coast of the U.S. Proc. Symposium on Mollusca Part III. pp. 925-948, 1970.

Miller, C.B. The Zooplankton of Estuaries. In: Ecosystems of the World: Estuaries and Enclosed Seas, B.H. Ketchum, ed. Elsevier Scientific Publishing Company, New York, 1983. pp. 103-149.

Mills, W.B., J.D. Dean, D.B. Porcella, S.A. Gherini, R.J.M. Hudson, W.E. Frick, G.L. Rupp, and G.L. Bowie. Water Quality Assessment: A Screening Procedure for Toxic and Conventional Pollutants, Part 2. Prepared for ERL, Office of R and D, EPA, Athens, GA by Tetra Tech, Inc., Lafayette, CA, September 1982.

Misra, R.D. Edaphic factors in the distribution of aquatic plants in the English Lakes. J. Ecology 26:411-451, 1938.

Montagna, P.A. Sampling design and enumeration statistics for bacteria extracted from marine sediments. Appl. Environ. Microbiol., 43:1366-1372, 1982.

Muncy, R.J. Life History of the Yellow Perch, Perca flavescens, in Estuarine Waters of the Severn River, a Tributary of Chesapeake Bay, Maryland. Ches. Sci. 3:143-159, 1962.

NOAA. Tide Tables, for East and West Coasts of North America, USDC, Washington, D.C., 1983.

Norcross, J.J., S.C. Richardson, W.H. Massmann, and E.B. Joseph. Development of young bluefish (Pomatomus saltatrix) and distribution of eggs and young in Virginian coastal waters. Trans. Am. Fish. Soc. 103(3):477-497, 1974.

Ogden, E.C. The broad-leaved species of Potamogeton of North America and Mexico. Rhodora 45:57-105, 119-216, 1943.

Olla, B.L. and A.L. Studholme. Daily and seasonal rhythms of activity in the bluefish (Pomatomus saltatrix). Pages 303-326 in H.E. Winn and B.L. Olla, Eds. Behavior of marine animals. Vol. 2. Plenum Press, New York, 1979.

Ostenfeld, C.H. Report on the Danish oceanographical expeditions 1908-1910 to the Mediterranean and adjacent seas. Biology 2:16, 1918.

O'Connor, D.J., J.A. Muellar, and Farley, K.J. Distribution of Kepone in the James River Estuary. Journal of Environmental Engineering Division, ASCE, 109:396-413, 1983.

Pardue, G.B. Habitat Suitability Index Models: Alewife and Blueback Herring. U.S. Dept. Int. Fish Wildl. Serv., FWS/OBS-82/10.58, 1983.

Parker, J.C. The biology of the spot, Leiostomus xanthurus (Lacepede) and Altantic croaker, Micropogon undulatus (Linnaeus), in two Gulf of Mexico nursery areas. Sea Grant Publ. No. TA7U-SG-71-210. Texas A&M University, College Station, 1971.

Patten, B.C., Jr. Notes on the biology of Myriophyllum spicatum L. in New Jersey lake. Bull. Torrey Bot. Club 83:5-18, 1956.

Perkins, E.J. The Biology of Estuaries and Coastal Waters. Academic Press, New York, 1974.

Perkins, H.C. Air Pollution. McGraw-Hill Book Company, New York, 1974.

Perret, W.S., et al. Louisiana Wildlife and Fisheries Commission. Cooperative Gulf of Mexico Estuarine Inventory and Study, Louisiana, 1971.

Perret, W.S., B.B. Barrett, W.R. Latapie, J.F. Pollard, W.R. Mock, G.B. Adkins, W.J. Gaidry, and C.J. White. Fishes and invertebrates collected in trawl and seine samples in Louisiana estuaries. Pages 41-68 in Perret, et al., eds. Cooperative Gulf of Mexico estuarine inventory and study, Louisiana. La. Wildl. Fish. Comm., New Orleans, LA, 1971.

Perry, H.M. and D.L. Boyes. Menhaden and other coastal pelagic fish. Pages 169-206 in J.Y. Christmas, ed. Fisheries assessment and monitoring, Mississippi. Gulf Coast Research Lab., Ocean Springs, MS, 1978.

Perry, H.M. and J.Y. Christmas. Estuarine zooplankton, Mississippi. Pages 198-254 in J.Y. Christmas, ed. Gulf of Mexico estuarine inventory and study, Mississippi. Gulf Coast Research Lab., Ocean Springs, MS, 1973.

Peters, D.S. and M.A. Kjelson. Consumption and Utilization of Food by Various Postlarval and Juvenile Fishes of North Carolina Estuaries. In: Estuarine Research. L.E. Cronin, ed. Academic Press, Inc., New York. I:448-471, 1975.

Philipp, C.C. and R.G. Brown. Ecological studies of transition-zone vascular plants in the South River, Maryland. Chesapeake Sci. 6:73-81, 1965.

Phillips, R.C. Temperature grass flats. In: H.T. Odum, B.J. Copeland, and R.A. McMahan. Coastal ecological systems of the United States, Vol. 2, Conserv. Found., Washington, D.C., 1974. pp. 244-299.

Pristas, P.J. and T.D. Willis. Menhaden Tagging and Recovery. Marine Fisheries Review. 35:31-35, 1973.

Pritchard, D.W. Estuarine Circulation Patterns. American Society of Civil Engineer, 81, 1955.

Pritchard, D.W. Salinity Distribution and Circulation in the Chesapeake Bay Estuarine System. Journal of Marine Research , 11:106-123, 1952.

Radford, A.E., H.E. Ahles, and C.R. Bell. Manual of the vascular flora of the Carolinas. Univ. North Carolina Press, Chapel Hill, 1964.

Raffaelli, D.G. and C.F. Mason. Pollution monitoring with meiofauna, using the ratio nematodes to copepods. Mar. Pollut. Bull., 12:158-163, 1981.

Raney, E.C. and W.H. Massmann. The Fishes of the Tidewater Section of the Pamunkey River. J. Wash. Acad. Sci. 43:424-432, 1953.

Raschke, R.L. Macrophyton. In: WPCF Pre-Conference Workshop: Use Attainability Analysis. Atlanta, Georgia, 1983.

Rawls, C.K. Aquatic plant nuisances. Proc. Interstate Comm. Potomac River Basin 1:51-56, 1964.

Reish, D.J. Bristle Worms (Annelida: Polychaeta). In: Pollution Ecology of Estuarine Invertebrates, C.W. Hart, Jr. and S.L.H. Fuller, eds. Academic Press, New York, 1979. pp. 78-125.

Richett, H.W. A quantitative study of the larger aquatic plants of Green Lake, Wisconsin. Wisc. Acad. Sci. Arts Letters 21:381-414, 1923.

Rigter, B.P. Minimum Length of Salt Intrusion in Estuaries. Journal of Hydraulics Division, ASCE, 96:1475-1496, 1973.

Rodnick, K. and H.W. Li. Habitat Suitability Index Models: Littleneck Clam. U.S. Dept. Int. Fish Wildl. Serv. FWS/OBS-82/10.59, 1983.

Roesner, L.A., P.R. Giguere, and D.E. Evenson. Computer Program Documentation for the Stream Quality Model QUAL-II. Report No. EPA-600/9-81-014. Prepared for the Southeast Michigan Council of Government, Detroit, MI, and EPA, by Camp Dresser & McKee, Inc., Annandale, VA, January 1981.

Ross, B.E. and P.D. Jerkins, Computer Simulation of Nutrients in Tampa Bay, Florida, Structures, Materials and Fluids Department, College of Engineering, University of South Florida, Tampa, FL, August 1978.

Ross, B.E. and P.D. Jerkins. University of South Florida's Mathematic Bay Models. Dept. Civil Engineering, University of South Florida, Tampa, FL, February 1983.

Sandoz, M. and R. Rogers. The Effect of Environmental Factors on Hatching, Moulting and Survival of Zoea Larvae of the Blue Crab, Collinectes sapidus. Rathbun. Ecology. 25:216-228, 1944.

Sasser, C.E. Distribution of vegetation in Louisiana coastal marshes as response to tidal flooding. M.S. Thesis, LSU, Baton Rouge, LA, 1977.

Schinder, D.W. Two useful devices for vertical plankton and water sampling. J. Fish. Res. Board Can. 26:1948-1955, 1969.

Schuette, H.A. and H. Alder. Notes on the chemical composition of some of the large aquatic plants of Lake Mendota II. Vallisneria and Potamogeton. Trans. Wisconsin Acad. Sci. Arts Letters 23:249-254, 1927.

Sculthorpe, C.D. The biology of aquatic vascular plants. Edward Arnold Ltd., London, 1967.

Setzler, E.M., W.R. Boynton, K.N. Wood, H.H. Zion, L. Lubbers, N.K. Mountford, P. Frere, L. Tucker, and J.A. Mihursky. Synopsis of Biological Data on Striped Bass, Morone saxatilis (Walbaum). NOAA Tech. Report NMFS Circ. 433, 1980.

Shea, G.B., G.B. Mackiernan, L.C. Athanas, and D.F. Bleil. Chesapeake Bay Low Flow Study: Biota Assessment. Vol. III. Western Eco-systems Technology Phase I Final Report to U.S. Army Corps. Eng., Baltimore District, Baltimore, MD, 1980.

Shipp, R.L. Summary of knowledge of forage fish species of Mobile Bay and vicinity. Pages 167-176 in H.A. Loyacano, Jr., and J.P. Smith, eds. Symposium on the natural resources of the Mobile Estuary, Alabama. May 1979. U.S. Army Corps of Eng., Mobile, Alabama, 1981.

Sikora, W.B. and J.P. Sikora. Habitat Suitability Index Models: Southern Kingfish. U.S. Dept. Int. Fish Wildl. Serv. FWS/OBS-82/10.31, 1982.

Smayda, T.J. The Phytoplankton of Estuaries. In: Ecosystems of the World: Estuaries and Enclosed Seas, B.H. Ketchum, ed. Elsevier Scientific Publishing Company, New York, 1983. pp. 65-102.

Smith, P.E. and S.L. Richardson. Standard Techniques for pelagic fish egg and larva surveys. FAO Fish. Tech. Pap. (175):100 pp., 1977.

Southwick, C.H. Tentative outline for inventory of aquatic vegetation: Myriophyllum spicatum (Eurasian watermilfoil). Chesapeake Sci. 13 (suppl). S174-S176, 1972.

Springer, P.F. Summary of interagency meeting on Eurasian watermilfoil. U.S. Fish Wildl. Serv. Patuxent Wildl. Sta., Laurel, MD. Mimeo., 1959.

Springer, P.F., G.F. Beaven, and V.D. Stotts. Eurasian watermilfoil--a rapidly spreading pest plant in eastern waters. Northeast Wildl. Conf. Mimeo., 1961.

Springer, V.C. and K.D. Woodburn. An ecological study of the fishes of the Tampa Bay area. Fla. State Board Conserv. Mar. Res. Lab., Prof. Pap. Ser. 1, 1960.

Steedman, H.R. (ed.). Zooplankton fixation and preservation. Unesco Monogr. Oceanogr. Methodol., (4):350 pp.

Steenis, J.H. Status of Eurasian Watermilfoil and associated submerged species in the Chesapeake Bay area--1969. Adm. Rept. to R. Andrews, U.S. Fish Wildl. Serv. Patuxent Wildl. Research Sta., 1970.

Steenis, J.H., E.W. Ball, V.D. Stotts, and C.K. Rawls. Pest plant control with herbicides, pp. 140-148. In Proc. Marsh Estuary Mgt. Symp., Louisiana State Univ., Baton Rouge, 1967.

Steinbeck, J. and E. Picketts. Sea of Cortez. Viking Press, New York, 1941.

Stevenson, J.C. and N.M. Confer. Summary of Available Information on Chesapeake Bay Submerged Vegetation. U.S. Dept. of the Interior, FWS/OBS-78/66, 1978.

Stickney, R.R. and M.L. Cuenco. Habitat Suitability Index Models: Juvenile Spot. U.S. Dept. Int. Fish Wildl. Serv., Washington, D.C. FWS/OBS-82/10.20.

Stickney, R.R., G.L. Taylor, and D.B. White. Food Habits of Five Species of Young Southeastern United States Estuarine Sciaenidae. Ches. Sci. 16:104-114, 1975.

Stokes, G. Life history studies of Paralichthys lethostigma in the vicinity of the Aransas Pass, Texas. Ann. Rep. Fish. Div., Texas Parks and Wildlife Dept., Austin, Texas, 1973.

Stommel, H. and Farmer, H.G. On the Nature of Estuarine Circulation, Parts I and II, Woods Hole Oceanog. Inst., TR 52-63 and 52-88, 1952.

Stotts, V.D. Summary of the interagency research meetings on the biology and control of Eurasian watermilfoil. Md. Game Inland Fish Comm. Mimeo., 1961.

Swingle, H.A. and D.G. Bland. A study of the fishes of the coastal water-courses of Alabama. Ala. Mar. Resour. Bull. 10:17-102, 1974.

Tabb, Durbin C. A Contribution to the Biology of the Spotted Seatrout, Cynoscion nebulosus (Cuvier), of East-Central Florida. Florida State Board of Conservation, Technical Series. 35:1-23, 1961.

Teeter, J.W. Effects of sodium chloride on the sago pondweed. J. Wildl. Mgt. 29(4):838-845, 1965.

Tenore, K.R., J.H. Tietjen, and J.J. Lee. Effect of meiofauna on incorporation of aged eelgrass. Zostera marina, detritus by the polychaete Nepthys incisa. Journal of the Fisheries Research Board of Canada, 34:563-567, 1977.

Thatcher, M.L. and Harleman, D.R.F. Prediction of Unsteady Salinity Intrusion in Estuaries: Mathematical Model and User's Manual. Report No. 159, Parsons Lab., MIT, Cambridge, Massachusetts, November 1972, pg. 7.

Theiling, D.L. and H.A. Loyacano, Jr. Age and growth of red drum from a saltwater marsh impoundment in South Carolina. Trans. Am. Fish. Soc. 105(1):41-44, 1976.

Thomas, D.L. An Ecological Study of the Delaware River in the Vicinity of Artificial Island. Part III. The Early Life History and Ecology of Six Species of Drum (Sciaenidae) in the Lower Delaware River, a Brackish-Tidal Estuary. Progress Rep. for January-December, 1970. Ichthyological Assoc. Bull. 3, 1971.

Titus, J., R.A. Goldstein, M.S. Adams, J.B. Mankin, R.V. O'Neill, P.R. Weiler, Jr., H.H. Shucart, and R.S. Booth. A production model for Myriophyllum spicatum. Ecology 56:1129-1138, 1975.

Tranter, D.J. (ed.). Zooplankton sampling. Unesco Monogr. Oceanogr. Methodol., (2):174 pp., 1968.

Turner, R.E. and M.S. Brody. Habitat Suitability Index models: Northern Gulf of Mexico brown shrimp and white shrimp. U.S. Dept. of Int. Fish Wildl. Serv. FWS/OBS-82/10.54, 1983.

Tutin, T.G. The Percy Sladen Trust expedition to Lake Titicaca in 1937 the leadership of Mr. H. Cary Gibson. M.A.X. The macrophytic vegetation of the lake. Trans. Linnaean Soc. London, 3rd Ser. 1:161-189, 1940.

Uhlig, G., H. Thiel, and J.S. Gray. The quantitative separation of meiofauna. A comparison of methods. Helgolander wiss. Meeresunters., 25:173-195, 1973.

Ukeles, R. Nutritional Requirements for Shellfish Culture. In: Artificial Propagation of Commercially Valuable Shellfish. K. Price and D. Maurer, eds. University of Delaware, 1971.

Ungar, I.A. Inland halophytes of the United States, pp. 235-305. In R.J. Reimold and W.H. Queen eds., Ecology of halophytes. Academic Press, Inc., New York, 1974.

U.S. Army Corps of Engineers, Baltimore District. Chesapeake Bay, existing conditions report. Vol. 1-7, 1974.

U.S. Department of Interior, Fish and Wildlife Service. Propagation of wild duck foods. Wildl. Mgt. Series I, 1944.

U.S. Dept. of the Interior. National Estuary Study, Volume 2, U.S. Govt. Printing Office, Washington, D.C., 1970.

U.S. Environmental Protection Agency. Techniques for sampling and analyzing the marine macrobenthos. EPA-600/3-78-030, 1978.

U.S. Environmental Protection Agency. Chesapeake Bay Program Technical Studies: A Synthesis. Washington, D.C., 1982.

U.S. Environmental Protection Agency. Chesapeake Bay: A Profile of Environmental Change, text and appendices. Washington, D.C., 1983a.

U.S. Environmental Protection Agency. Technical Support Manual: Waterbody Surveys and Assessments for Conducting Use Attainability Analyses. Washington, D.C., 1983b.

U.S. Environmental Protection Agency. Chesapeake Bay: A Framework for Action, text and appendices. Washington, D.C., 1983c.

U.S. Geological Survey. Water Resources Data Virginia Water Year 1981. U.S. Dept. of the Interior, 1982.

Van Engel, W.A., D. Cargo, and F. Wojecek. The Edible Blue Crab--Abundant Crustacean. Leaflet 15. Marine Resources of the Atlantic Coast. Atlantic States Marine Fisheries Commission. Washington, D.C., 1973.

Vernberg, W.B. Responses to Estuarine Stress. In: Ecosystems of the World: Estuaries and Enclosed Seas, B.H. Ketchum, ed. Elsevier Scientific Publishing Company, New York, 1983. pp. 43-63.

Wallace, D.E., R.W. Hanks, H.T. Pfitzenmeyer, and W.R. Welch. The Soft Shell Clam ... A Resource with Great Potential. Marine Resources of the Atlantic Coast Leaflet No. 3, Atlantic States Marine Fisheries Comm., Tallahassee, FL, 1965.

Wallace, D.H. Sexual Development of the Croaker, Micropogon undulatus, and Distribution of the Early Stages in Chesapeake Bay. Trans. Am. Fish. Soc. 70:475-482, 1940.

Walton, R., J.A. Aldrich, and R.P. Shubinski. Chesapeake Bay Circulation Model: Final Report. Prepared for EPA, Chesapeake Bay Program, Annapolis, MD, by Camp Dresser & McKee, Inc., Annandale, VA, January 1983.

Wang, J.D. and J.J. Connor. Mathematical Modeling of Near Coastal Circulation. Ralph M. Parsons Lab., M.I.T. Report No. 200, April 1975.

Warwick, R.M. The nematode/copepod ratio and it's use in pollution ecology. Mar. Pollut. Bull., 12:329-333, 1981.

White, D.C., R.J. Bobbie, J.D. King, J.S. Nickels, and P. Amoe. Lipid analysis of sediments for microbial biomass and community structure, p. 87-103. In: C.D. Litchfield and P.L. Seyfried (eds.), Methodology for biomass determinations and microbial activities in sediments. Publ. No. ASTM STP 673, American Society for Testing and Materials, Philadelphia, 1979.

Wilk, S. Biological and fisheries data on bluefish, Pomatomus saltatrix (Linnaeus). National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Center, Tech. Ser. Rep. 11, 1977.

Wilkinson, R.E. Effects of light intensity and temperature on the growth of waterstargrass, coontail, and duckweed. Weeds 11:287-289, 1963.

Wilk, S.J. Biology and Ecology of the Weakfish, Cynoscion regalis, Bloch and Schneider. In: Proceedings of the Colloquium on the Biology and Management of Red Drum and Seatrout. Gulf States Marine Fisheries Commission, 1978.

Williams, A.B. and T.W. Duke. Crabs (Arthropoda: Crustacea: Decapoda: Brachyura). In: Pollution Ecology of Estuarine Invertebrates. C.W. Hart, Jr. and S.L.H. Fuller, eds. Academic Press, New York, 1979. pp. 171-234.

Wolff, W.J. Estuarine Benthos. In: Ecosystems of the World: Estuaries and Enclosed Seas, B.H. Ketchum, ed. Elsevier Scientific Publishing Company, New York, 1983. pp. 151-182.

Yeo, R.R. Yields of propagules of certain aquatic plants. I. Weeds 14:15:110-113, 1965.

Zenkevitch, L.A. Biology of the seas of the U.S.S.R. Interscience Pub., New York, 1963.

Zison, S.W., Hewen, K.F., and Mills, W.B. Water Quality Assessment: A Screening Method for Nondesignated 208 Areas. Prepared for EPA, Office of Rand D, EPA, Athens, GA, by Tetra Tech. Inc., Lafayette, California, August 1977.

APPENDIX A

DEFINITION OF THE CONTAMINATION INDEX (C_I) AND THE TOXICITY INDEX (T_I)

To assess the contribution of anthropogenic sources of metal contamination over time, sediment cores may be analyzed. The Wedepohl ratio compares the amount of metal in the sediment sample with the concentration in an average shale (or sandstone). In the Chesapeake Bay program, scientists have measured silicon and aluminum, then correlated metals with Si/Al ratios. A contamination factor (Cf) may be computed as follows:

$$Cf = (Co-Cp)/Cp$$

where: Co = surface sediment concentration
Cp = predicted concentration, derived from the statistical relation between the Si/Al ratio and the log metal content of old, pre-pollution sediments from the estuary.

Thus, Cf < 0 when the observed metal concentration is less than the predicted value; Cf = 0 when observed and predicted are the same; Cf > 0 when the observed is greater than the predicted value.

The Contamination Index (C_I) is found by summing contamination factors for metals in a given sediment.

Then,

$$C_I = \sum_{n=1}^{n} Cf = \sum_{n=1}^{n} (Co-Cp)/Cp$$

The Toxicity Index (T_I) is related to the Contamination Index and is expressed by the following equation:

$$T_I = \sum_{i=1}^{i} (M_1/M_i) \cdot Cf_i$$

where: M_i = the "acute" anytime EPA criterion for any of the metals,
but M_1 is always the criterion value for the most toxic of the metals.

The "acute" anytime EPA criterion is defined as the concentration of a material that may not be exceeded in a given environment at any time. When evaluating Toxicity Indices, sampling stations should be characterized by their minimum salinities. This is because the toxicity of metals is often greater in freshwater than in saltwater.

A more detailed discussion of the development of the Contamination Index may be found in the U.S. EPA publication, Chesapeake Bay: A Profile of Environmental Change (1983a) and A Framework for Action (1983c).

APPENDIX B

LIFE CYCLES OF MAJOR SPECIES OF ATLANTIC COAST ESTUARIES

Contents

(from U.S.EPA 1983a)

TABLE 1a. ENVIRONMENTAL TOLERANCES OF ALOSA AESTIVALIS (BLUEBACK HERRING) CANADIAN MARITIMES TO ST. JOHN'S RIVER, FL

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	Tidal-fresh and low-brackish water. Eggs are found in streams and rivers with swift currents and sandy or rocky substrate.	Not applicable	No information	Not applicable	No information	Burbidge 1974 Hudson and Hardy 1974 Jones et al. 1978 Lippson et al. 1979
Larvae	Tidal-fresh and brackish water. Larvae are found in tributary streams and upper portions of rivers. Optimum salinity 0-5 ppt.	- copepods	Growth occurs during warm temperatures.	Interspecific competition with Bay anchovy in brackish water causes larvae to select food items other than the preferred type.	Compete with Bay anchovy. Prey of predatory fish (striped bass, white perch)	Domermuth and Reed 1980 Raney and Massmann 1953
Juvenile	Tidal-fresh and brackish water. Juveniles are found primarily in surface waters. Tolerate salinity 0-28 ppt. Optimum salinity 0-5 ppt.	Selective feeder during daylight. - copepods - copepodites - Bosmina spp. - macrozooplankton	Growth occurs during warm temperatures; rate of growth is more rapid than for alewives.	Young juveniles remain in nursery area until the fall, then undertake a seaward migration. Young may remain in the lower Bay during first or second winter.	Prey of predatory fish (striped bass, white perch, bluefish)	
Adult	0-34 ppt salinity. Adults enter the Bay to spawn in freshwater; return to the ocean after spawning.	- zooplankton - crustaceans - crustacean eggs - insects - fish eggs and larvae	Blueback herring mature in 3-4 yrs., and reach a maximum length of 38.0 cm.	Schooling herring occur in a narrow band of coastal water; move to the bottom during winter. Herring are anadromous, migrating into the Bay to spawn in spring.	Prey of predatory fish (striped bass, bluefish, weakfish) in fresh, brackish, & salt water. Target of a commercial & recreational fishery.	

TABLE 1b. ENVIRONMENTAL TOLERANCES OF ALOSA PSEUDOHARENGUS (ALEWIFE) NEWFOUNDLAND TO SOUTH CAROLINA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	0-0.5 ppt salinity. Eggs are released in slow, shallow portions of creeks and rivers over detritus or sandy substrate.	Not applicable	Hatching period 6 days. Mean water temp. 60°F.	Not applicable	No information	Jones et al. 1978 Shea et al. 1980 Lippson et al. 1979 Hildebrand and Schroeder 1928
Larvae	0-3 ppt salinity. Larvae remain in vicinity of spawning area at depths less than 3m.	- rotifers - copepod nauplii	No information	Form schools within 1-2 days after hatching.	Prey of predatory fish (white perch and striped bass)	
Juvenile	Tolerate salinity 0-34 ppt. Optimum salinity 0.5-5 ppt. Young juveniles are found in nursery areas from shore to shore; as the fish grow, there is a slow downstream movement.	- copepods - mysid shrimp	Grow very rapidly, possibly due to entering salt water, average 105 mm.	Young juveniles migrate toward the ocean in the fall, some overwinter in deep areas of the Bay.	Prey of predatory fish (bluefish, striped bass, white perch)	
Adult	0-34 ppt salinity. Adults enter the Bay to spawn in freshwater; return to ocean by mid-summer.	Mid-water feeder - copepods - young fish - zooplankton - mysids	Alewife mature in 3-4 yrs., measuring an average 25.0-30.0 cm in length.	Schooling alewife show regular anadromous Alosid coastal movements. Alewife are anadromous, migrating into the Bay to spawn in spring.	Prey of predatory fish (striped bass, bluefish, weakfish). In fresh, brackish, and salt water. Target of commercial and recreational fishery.	

TABLE 1c. ENVIRONMENTAL TOLERANCES OF *ALOSA SAPIDISSIMA* (AMERICAN SHAD) GULF OF ST. LAWRENCE TO FLORIDA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	0-0.5 ppt salinity. Streams and rivers with swift currents and sandy or rocky substrate.	Not applicable	Temperatures above 21°C and low D.O. levels decrease hatching success.	Not applicable	No information	Hildebrand and Schroeder 1928 Shea et al. 1980 Domermuth and Reed 1980
Larvae	Optimum salinity 0-5 ppt. Larvae are found at depths greater than 3m.	No information	At D.O. levels of 5 ppm, some stress and mortality occurs; at D.O. levels of 4 ppm, high mortality may occur.	No information	Preyed upon by top predatory species (striped bass, bluefish, white perch, other herring spp.)	Lippson et al. 1979 Ellis et al. 1947
Juvenile	Tolerate salinity 0.5-12 ppt. Optimum salinity 5-12 ppt. Young juveniles gradually move into more saline waters.	Feed at or beneath surface - daphnid cladocerans - bosminid cladocerans - other cladoceran spp. - copepods	Young grow rapidly during the first summer.	Juveniles remain in natal streams and rivers until the fall, then undertake a seaward migration. Some remain in the lower Bay during the first winter.	Competition with species such as the alewife or blueback herring influence location of feeding fish & selection of prey. Prey of top predatory species.	
Adult	Tolerate salinity 0-30 ppt. Adults enter the Bay to spawn in freshwater or on flats in tidal waters; return to ocean after spawning.	Feed in surface layer - copepods - small fish - planktivorous crustaceans - insects	Growth rate decreases after 3 years of age. Reach sexual maturity in 4-5 years.	Shad are anadromous, migrating into the Bay to spawn in spring. Nests are built, but no parental care is given to eggs.	Prey of top predatory fish (bluefish, striped bass). Target of a commercial and recreational fishery.	

TABLE 1d. ENVIRONMENTAL TOLERANCES OF BREVOORTIA TYRANNUS (ATLANTIC MENHADEN) NOVA SCOTIA TO GULF OF MEXICO

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	Eggs are released in the ocean, probably not far (as far as 64 km) from the mouth of the Bay.	Not applicable	No information	Not applicable	No information	Pristas and Willis 1973 Shea et al. 1980 June and Carlson 1971 Durbin and Durbin 1975 Lippson et al. 1979
Larvae	Early larvae tolerate 18-34 ppt salinity. Optimum salinity 25-34 ppt. Later they concentrate in tidal fresh to low brackish waters (0-3 ppt salinity).	Sight-selective feeders - copepods size of fish influences size of copepods taken.	No information	Larvae enter the Bay in spring when they are about 10-30 mm long; may reach nursery areas in larval or juvenile stage.	No information	
Juvenile	Tolerate salinity 0-34 ppt. Optimum salinity 0-15 ppt. Younger fish concentrate in tidal-fresh to low-brackish waters.	Filter feeder - phytoplankton	No information	Young-of-the-year juveniles remain in the Bay during summer; may leave in fall or over-winter in Bay.	Prey of top predatory fish including bluefish and striped bass.	
Adult	Tolerate salinity 1-36 ppt concentrate in areas of 5-18 ppt salinity where food patches occur. One and two year old adults utilize the Bay; older fish remain off the coast.	Filter feeder - zooplankton - larger phytoplankton - longer chains of chain-forming diatoms. Feeding behavior is linked to food density and particle size.	Some fish may reach maturity in one year; all fish are mature by age 3. Maximum length around 47.0 cm.	Schooling marine fish which enter the Bay in spring to feed; most migrate seaward in the fall, though some may overwinter in the lower Bay.	Prey of top predatory fish including bluefish and striped bass. Target of a commercial fishery.	

TABLE 1e. ENVIRONMENTAL TOLERANCES OF CALLINECTES SAPIDUS (BLUE CRAB) NEW JERSEY TO FLORIDA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	Hatch at salinities of 10.3-32.6 ppt; optimum salinities for hatch are 23-30 ppt. Females carry the eggs until hatch occurs.	Not applicable	Salinity affects hatching success.	Not applicable	No information	Van Engel et al. 1973 Shea et al. 1980 Bulkin 1975 Van Engel 1958
Zoeae	Tolerate salinities of 15.8-32.3 ppt; optimum salinities are 21-28 ppt. Zoeae are found in the upper surface water.	- rotifers - Nauplii larvae - sea urchin larvae - polychaete larvae	Zoeae molt at least three times, with the final mold producing a megalops. Molting is affected by salinity, temperature, larval concentrations, and light intensity.	Zoeae show an attraction to light.	No information	Sandoz and Rogers 1944 Lippson 1971 Lippson et al. 1979
Megalops	Optimum salinities of 20-35 ppt. Megalops may be found in surface waters or on the bottom.	Omnivorous - plants - fish and shellfish pieces - detritus Availability of prey affects diet.	Salinity and temperature affect the duration of the megalops stage. Megalops metamorphose into a small juvenile crab.	Megalops and juveniles move into the Bay through the entrainment in bottom waters, beginning in fall. In winter young crabs cease migrations and burrow into channel bottoms.	No information	
Juveniles and Adults	Juveniles concentrate in brackish water with salinities less than 20 ppt. Adult males concentrate in salinities of 3-15 ppt. Females concentrate in salinities of 10-28+ ppt.	- benthic organisms - small fish - plants - shellfish - small crustaceans - detritus Availability of prey affects diet.	Crabs reach sexual maturity in 12-20 months depending on timing of hatch. Growth occurs by shedding the shell, and is regulated by water temperature.	In warm weather, juveniles move inshore. When temperatures drop, juveniles move to channel areas to overwinter in semi-hibernation. Adults have similar movement patterns.	- predatory fish such as striped bass and bluefish - birds such as herons and herring gulls - a commercial and recreational fishery.	

TABLE 1f. ENVIRONMENTAL TOLERANCES OF CRASSOSTREA VIRGINICA (AMERICAN OYSTER) NEW ENGLAND TO GULF COAST

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	Optimum salinity of 22.5 ppt; below 10 ppt, survival is poor. Pelagic eggs released in open water.	Not applicable	Turbidity levels of 125 mg L^{-1} or more reduce development and survival of eggs.	Not applicable	No information	Galtsoff 1964 Haven and Morales-Alamo 1970 Korringa 1952 Davis and Calabrese 1964 Ukeles 1971 Andrews 1967, 1968 Haven, personal communication
Larvae	Optimal growth occurs at salinities of 12.5-25.0 ppt.	Filter feeder - phytoplankton - bacteria The size of food particles taken is a function of the mouth size.	Turbidity levels of 100 mg L^{-1} cause high larval mortality. Salinity, temperature, and available food influence larval development.	Oyster larvae move within the estuary by entrainment in bottom waters. Larvae search for suitable substrate on which to attach in about two weeks. At setting, larvae metamorphose to spat.	Prey of planktonic-feeding fish and invertebrates.	
Juveniles (spat)	Salinity 5-35 ppt. Oysters are found in shallow water less than 10 meters deep. Optimum survival of oysters occurs on hard substrate such as rocks, pilings, and oyster shells in the intertidal and sub-tidal zones.	Filter feeder - phytoplankton - bacteria - detritus	Spat exhibit rapid growth during the first year. Growth rates are affected by availability of food, salinity, and water temperature.	Oysters initially develop as males, yet by the second breeding season many change into females.	Competitors - boring sponges and clams - slipper shell - sea squirt - barnacles - spirochaetes - perforating algae Predators - oyster drills - blue crabs - starfish - birds - commercial fishery Diseases - *Perkinsus marinus* (Dermo) - *Menchinia nelsoni* (MSX)	
Adults		Filter feed on 1-12 micron prey - phytoplankton - bacteria - detritus Turbidity and low temperatures influence feeding and digestion.	Growth is affected by substrate type, salinity, temperature, tidal flow, and crowding. Oysters reach sexual maturity during the second year of growth. [A few reach maturity at one year (Haven)]	Epibenthic with frequent alternation of sex. Form communities or "bars." Oyster distribution in higher salinity areas is restricted by predators and parasites.		

TABLE 1g. ENVIRONMENTAL TOLERANCES OF CYNOSCION REGALIS (WEAKFISH) MASSACHUSETTS TO FLORIDA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	Tolerate salinities of 5-34 ppt. Buoyant eggs are released in the nearshore and estuarine zones along the coast.	Not applicable	Eggs are susceptible to low D.O. levels and sudden changes in either salinity or temperature.	Not applicable	No information	Lippson et al. 1979 Daiber et al. 1976 Wilk 1978 McHugh 1978
Larvae	Tolerate salinities 12-31 ppt. Larvae remain in the general vicinity of spawning.	No information	Larvae cannot withstand sudden changes in either salinity or temperature; a 5°C change in temperature in either direction can be fatal.	No information	No information	
Juvenile	About 0-34 ppt salinity. Young-of-the-year fish move into low salinity areas over soft, muddy bottoms.	- shrimp - other crustacean spp. - bay anchovy - young menhaden - other small fish	Weakfish grow most rapidly during their first year, reaching an average length of 19 cm.	Young juveniles move into low salinity areas for the summer; migrate to the coast in fall, and move offshore and south in the winter. Begin schooling as pre-adults.	Preyed upon by bluefish, striped bass, and large weakfish.	
Adult	Tolerate salinities of 10-34 ppt. Adults remain in the lower portion of the Bay.	Primarily piscivorous - menhaden - herring spp. - bay anchovy - silversides - crustaceans - annelids	Weakfish are sexually mature in 2-3 years, and reach an average length of about 50.0 cm.	Adults school, arrive in Bay in spring, leave by late fall and head south and offshore for the winter; return north to inshore areas in spring.	Preyed upon by bluefish and striped bass. The target of a commercial and recreational fishery.	

TABLE 1h. ENVIRONMENTAL TOLERANCES OF CYNOSCION NEBULOSUS (SPOTTED SEATROUT) DELAWARE TO MEXICO

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	Spawning occurs at salinities of 30-35 ppt. Hatched in 40 hrs at 25°C. Eggs reported as both demersal and pelagic, released in deeper channels and holes adjacent to grassy bays and flats.	Not applicable	Eggs are susceptible to low D.O. and sudden changes in salinity or temperature.	Not applicable	No information	Tabb 1961 Arnold et al. 1978 Fable et al. 1978 Idyll and Fahy 1975 Lorio and Perret 1980
Larvae	Growth of larvae is rapid, about 4.5 mm in 15 days after hatching. Young fish spend their juvenile life in vegetated flats, moving to deeper water in winter.	Very small invertebrates, including copepods, mysid shrimp, and postlarval penaeid shrimp.	Highly sensitive to changes in temperature. Winter-time cold shock and high temperature changes causes kills.	Tend to remain close to site of spawning in grassy flats.	No information	
Juvenile	Fish larger than 2 inches show a tendency to congregate in schools. Remain in grassy, shallow water flats until colder weather causes them to move to deeper water.	As the trout grow, diet changes to include larger portions of caridean shrimp and then to penaeid shrimp.	Females grow faster than males but males attain sexual maturity at a smaller size. Growth is rapid in first year with lengths of 13 cm attained by the first winter and 25 cm their second winter.	Start to school as young fish but remain in general area of nursery grounds until cold weather causes them to move to deeper water.	Reported as highly cannibalistic in the postlarval stage.	

(continued)

TABLE 1h. (CONTINUED)

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Adult	While tagging studies show that some seatrout travel as much as 315 miles, most studies show that few fish leave their natal estuary. C. nebulosus occupies a more southern, warmer water habitat than does C. regalis.	Listed as the top carnivore in most estuarine communities. As an adult, will eat all other fish of a smaller size as well as shrimp and small crabs.	Longevity indicated to be 8 to 9 years of age. Generally mature at one to three years with 50% sexually mature by end of second year (25 cm in length). All fish appeared to have spawned by age three. A 1978 report cites the largest seatrout caught was 16 pounds.	Movemest patterns have been traced to the presence or absence of penaeid shrimp. Seasonal movements correspond to water temperature and spawning season.	A top predator which would be in competition with other predators such as bluefish and striped bass. both commercial and recreational fisheries.	

TABLE 1i. ENVIRONMENTAL TOLERANCES OF ICTALURUS CATUS (WHITE CATFISH) NEW YORK TO FLORIDA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Egg	Freshwater Eggs deposited in nests built near sand or gravel banks in still or running water.	Not applicable	Eggs need to be aerated.	Not applicable	No information	Jones et al. 1978 Lippson et al. 1979
Larvae	In freshwater, may move into tidal water.	No information	Yolk sac larvae bypass larval stage, develop directly to juvenile stage.	No information	No information	Daiber et al. 1976 Kendall and Schwartz 1968
Juvenile	No information	No information	Growth continues at 11 ppt salinity or less.	Remain in schools until end of first summer; initially guarded by parents.	No information	
Adult	Maximum salinity of 14.5 ppt Widespread in Bay. Prefer heavily silted bottom. Inhabit river channels and streams with slow current, ponds, and lakes.	Omnivorous, solitary, bottom feeder -plant material -small fish -clams and snails -worms -insects -dead material	Fish mature in one to two years. Maximum length 61.0 cm.	Stay in waters greater than 3 m, overwinter in deeper water (15 m), move upstream to spawn in freshwater. Males guard and aerate egg masses.	No information	

TABLE 1j. ENVIRONMENTAL TOLERANCES OF *ICTALURUS NEBULOSUS* (BROWN BULLHEAD) SOUTHERN CANADA TO SOUTHERN FLORIDA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Egg	Freshwater Eggs deposited in nests in sand or gravel at depths of several inches to several feet.	Not applicable	Eggs exposed to direct sunlight produce poor hatches. Eggs need to be agitated.	Not applicable	No information	Jones et al. 1978 Lippson et al. 1979 Daiber et al. 1976
Larvae	Freshwater Found at bottom	No information	Yolk-sac larvae bypass larval stage, develop directly to juvenile stage.	Grouped in a tight mass at bottom.	No information	
Juvenile	Found among vegetation or other cover over muddy bottoms.	No information	No information	Young juveniles herded in schools by parents; may remain in schools throughout first summer.	No information	
Adult	Adults are widespread throughout most of the Bay area, occurring in channels and shallow, muddy water around aquatic vegetation. Maximum salinity 10 ppt.	Omnivorous, solitary bottom feeder - plant material - small fish - clams and snails - worms - insects - dead material	Mature at 3 years. Maximum length around 50.8 cm.	A schooling bottom species which is active primarily at night. Fish may burrow in soft sediments. Adults attend eggs and orally agitate.	No information	

TABLE 1k. ENVIRONMENTAL TOLERANCES OF *ICTALURUS PUNCTATUS* (CHANNEL CATFISH) HUDSON BAY REGION TO NORTHERN MEXICO

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Egg	Eggs 1 to 2 days old tolerate salinity to 10 ppt; 3 days and older 16 ppt.	Not applicable	No information	Not applicable	No information	Jones et al. 1978 Lippson et al. 1979 Daiber et al. 1976
Larvae	Tolerate salinities up to 8 ppt.	No information	Abnormal development occurs at temperatures above 35°C. Yolk-sac larvae bypass larval stage, develop to juvenile stage.	Larvae guarded by male first few days after hatching.	No information	
Juvenile	Tolerate salinities up to 11-12 ppt.	Feed at surface	Growth continues at 11 ppt salinity or less.	Remain in schools up to several weeks. Show strong schooling and hiding tendencies in first year.	No information	
Adult	Maximum salinity of 21.0 ppt, prefer less than 1.7 ppt. Restricted distribution in Bay. - deeper channels of large rivers with sluggish or swift current.	Omnivorous, solitary, bottom feeder - plant material - small fish - clams and snails - worms - insects - dead material	Mature in 2 to 9 years. Maximum length around 120.2 cm.	Males construct nests and guard eggs.	No information	

TABLE 1 1. ENVIRONMENTAL TOLERANCES OF LEIOSTOMUS XANTHURUS (SPOT) MASSACHUSETTS TO FLORIDA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Egg	Eggs are released over the continental shelf.	Not applicable	No information	Not applicable	Jellyfish, such as the sea walnut (*Mnemiopsis leidyi*), predatory marine fish.	Hudson and Hardy 1974 Shea et al. 1980 Lippson et al. 1979
Larvae	Tolerate salinity 0-35 ppt. Optimum salinity 0-5 ppt in the estuary.	Sight-selective feeder - planktonic copepods	No information	No information	Prey of predatory fish and birds	Thomas 1971 Chao and Musick 1977
Juvenile	Tolerate salinity 0-34.2 ppt. Post-larvae and young fish concentrate at salinities of 0.5-5.0 ppt; during years of high population density young may move into freshwater. Prefer muddy substrate.	Bottom feeder - benthic harpacticoid copepods - annelids - plant material	Growth during first summer is rapid, juveniles may measure 13 cm by late fall.	Post-larvae are carried into the Bay in April through entrainment in bottom waters. School along shore during summer. Young move downstream as they grow.	Same as above	Peters and Kjelson 1975
Adult	8-34 ppt salinity. Occur at depths greater than 1 m over soft muddy bottom; larger fish prefer channel waters.	Bottom feeder - burrowing polychaetes - annelids - small crustaceans - molluscs - macrozooplankton	Reach sexual maturity by the third year; maximum length around 33-35 cm.	Adults enter the Bay in April and May, leave for spawning grounds offshore from Aug. through Nov.	Prey of large gamefish (striped bass), sharks, and the target of recreational and commercial fisheries.	

TABLE 1m. ENVIRONMENTAL TOLERANCES OF *MERCENARIA MERCENARIA* (HARD CLAM) NOVA SCOTIA TO YUCATAN

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	Tolerate 20-35 ppt salinity, prefer 26.5-27.5 ppt.	Not applicable	Salinity affects egg development.	Eggs are carried on currents in the Bay.	No information	Lippson 1973 Daiber et al. 1976
Larvae	Salinities greater than 17.5 ppt. Larvae are pelagic, found in the surface waters.	No information	Larval development is affected by salinity, temperature, turbidity, and circulation patterns.	Larvae are initially pelagic, but toward the end of this stage, they alternate between a planktonic and benthic existence.	Clam larvae are prey of other filter feeding organisms.	Shea et al. 1980 Castagna and Chanley 1973
Juvenile	Optimum salinity 24-28 ppt, survive salinities as low as 12.5 ppt.	Filter feeder - algae species - detritus	Growth rates vary with the type of substrate used; faster growth occurs in coarser sediments.	Young clams have bisexual gonads, usually dominated by male characteristics. After the first spawning season, about 50% of the juveniles become female.	Predators include - oyster drills - blue crabs - moon snails - conchs - horseshoe crabs - sea stars - puffers - waterfowl	
Adult	Salinities greater than 15 ppt. Hard clams occur in subtidal or intertidal waters with solid substrate (shell or rock).	Filter feeder - algae species	Large clams measure 12-13 cm in length.	Adults spawn during neap tides; spawning may be both thermally and chemically stimulated.	- cow nosed rays - drum fish - man	

TABLE 1n. ENVIRONMENTAL TOLERANCES OF <u>MICROPOGONIAS UNDULATUS</u> (ATLANTIC CROAKER) CAPE COD, MA TO FLORIDA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	Eggs are released in the ocean near the mouth of the Bay from August through December.	Not applicable	No information	Not applicable	No information	Shea et al. 1980 Hildebrand and Schroeder 1928 Lippson et al. 1979
Larvae	Larvae which enter the Bay in fall remain in channel waters at depths greater than 3m; carried to the salt water interface.	No information	No information	Larvae begin entering the Bay in fall through entrainment in bottom waters.	No information	Stickney et al. 1975 Chao and Musick 1977 Haven 1957
Juvenile	Young juveniles are found in channel waters of 0-21 ppt salinity. Older fish tend to be down-river from the younger fish.	Juveniles less than 10 cm - harpacticoid copepods Older juveniles - polychaetes - crustaceans - fish - other invertebrates	No growth occurs during the winter season; young fish have been killed during intensive cold periods on the nursery grounds.	Yearling croaker leave in the fall.	Striped bass predation on overwintering juveniles may depress the population; juveniles also preyed on by bluefish.	Joseph 1972 Wallace 1940
Adult	Tolerate salinity 0-40 ppt. *Optimum* salinity 10-34 ppt. Hard bottom at depths greater than 3m.	- small crustaceans - annelids - mollusca - small fish	Croaker reach a *maximum length of* around 50 cm.	Croaker enter the Bay in spring, remaining in the lower estuary until fall, then they migrate back to sea. Water temperature influences croaker migrations.	Prey of top predatory species (striped bass and bluefish). The target of a commercial and recreational fishery.	

TABLE 1o. ENVIRONMENTAL TOLERANCES OF *MORONE AMERICANA* (WHITE PERCH) NOVA SCOTIA TO SOUTH CAROLINA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Egg	Tolerate salinity 0-6 ppt. Eggs are released in tidal-fresh to low-brackish waters in shallows along the shore.	Not applicable	Suspended sediment levels about 1500 ppm increase incubation period.	Not applicable	No information	Shea et al. 1980 Lippson et al. 1979 Hildebrand and Schroeder 1928
Larvae	Tolerate salinity 0-8 ppt, prefer 0-1.5 ppt. Maximum depth 12 ft. Larvae are found in shallow water over sand or gravel bars or mud bottom.	Sight-selective feeders - rotifers - cladocerans - copepods	Temperature and availability of rotifers affects development of yolk-sac larvae.	Remain in spawning area, settle to bottom. General downstream movement as larvae develop.	Compete with striped bass larvae in nursery areas. Preyed upon by fish (striped bass) and birds.	Hudson and Hardy 1974 Loos 1975 Mansueti 1961
Juvenile	Tolerate salinity 0-13 ppt, prefer 0-3 ppt. Found in shallow sluggish water over silt, mud, or vegetation; move to sandy shoals and beaches at night.	- copepods - cladocerans - insect larvae	Growth positively correlated with temperature and solar radiation. Growth influenced by population density.	Juveniles remain in nursery area at least until 20 mm long, may remain until 1 year old. Juveniles may form large schools.	Compete with striped bass juveniles. Preyed upon by fish (striped bass, bluefish) and birds.	
Adult	Tolerate salinity 0-30 ppt, prefer 4-18 ppt. In summer, concentrate near shoals, occasionally in channel areas. In winter, found in deeper water; move to channels during coldest periods.	Bottom oriented, piscivorous - smelt - yellow perch - young eels - young striped bass - insects - crustaceans	Growth rates decrease with age and high population density. Males mature in 2 years, females in 3.	Schooling adults are resident to the Bay. White perch are semi-anadromous, making spawning migrations upstream in spring.	Preyed on by larger fish (striped bass, bluefish). Also the target of a commercial and recreational fishery.	

TABLE 1p. ENVIRONMENTAL TOLERANCES OF MORONE SAXATILIS (STRIPED BASS) ST. LAWRENCE RIVER, CANADA TO ST. JOHN'S RIVER, FL

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Egg	Tolerate salinity 0-10 ppt. 1.5-3 ppt optimal. 1.0-2.0 m sec^{-1} optimum flow rate. Semi-buoyant eggs released in fresh to brackish water.	Not applicable	Salinity and temperature influence development.	Not applicable	Prey of white perch.	Setzler et al. 1980 Boynton et al. 1981 Beaven and Mihursky 1980
Larvae	Tolerate salinity 0-15 ppt. 5-10 ppt optimal. 0.3-1.0 m sec^{-1} optimal flow rate. - open waters - at 13 mm, move inshore for first summer	Sight selective feeder - copepods - rotifers - cladocerans High prey concentrations necessary for successful first feeding.	Temperature and adequate food influence growth.	Positively phototrophic; newly-hatched larvae sink between swimming efforts; at 2-3 days of age larvae can swim continuously.	Compete with white perch larvae in nursery area.	Hollis 1952 Doroshev 1970 Shea et al. 1980 Md. Dept. Nat. Res. 1981
Juvenile	Juveniles 50-100 mm. Tolerate salinity 0-35 ppt. Optimal 10-20 ppt. 0-1 m sec^{-1} optimal flow rate. - prefer sandy substrate but found over gravel bottoms as well in shallow waters.	Non-selective feeder - insect larvae - polychaetes - larval fish - amphipods - mysids	Temperature and population density influence growth.	Downstream movement of young-of-the-year fish. Yearlings school in rivers or move into lower estuary in summer.	Compete with white perch in nursery Prey of predatory fish, birds, mammals, and man.	
Adult	Tolerate 0-35 ppt, usually in salinities greater than 12 ppt. Summer habitat includes high energy shorelines with a current. Overwinter in channels in estuary or offshore at depths below 6 m.	Piscivorous - alewife - blueback herring - white perch - spot - menhaden - bay anchovy - croaker	Temperature, age, population density, and oxygen levels influence growth.	Andromous, migrate to freshwater to spawn, return to lower estuary or ocean after spawning. Young females (2-3 yr) migrate along coast in summer with older fish.	Compete with bluefish, weakfish, and white perch. Commercial and recreational fishery for striped bass.	

TABLE 1q. ENVIRONMENTAL TOLERANCES OF *MYA ARENARIA* (SOFT SHELL CLAM) LABRADOR TO NORTH CAROLINA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	Eggs are released by sedentary adults in two spawning peaks, spring and fall.	Not applicable	No information	Not applicable	No information	Shea et al. 1980 Lucy 1977 Merrill and Tubiash 1970 Wallace et al. 1965 Castagna and Chanley 1973 Matthiessen 1960
Larvae	Minimum salinity for larval survival is 8 ppt.	Filter feeder - naked flagellates - other microscopic plankton spp.	Temperature influences larval development; at 10°C, larval development is slow.	After the planktonic larvae develop sufficiently, they metamorphose to adult form and settle to the bottom.	No information	
Juvenile	Juveniles occur over a broader depth range than adults.	Suspension feeder - phytoplankton - microzooplankton - bacteria - detritus	Juvenile clams are sensitive to salinity fluctuations.	Juveniles can move about by using the muscular foot or by currents. They establish a permanent burrow when one inch long.	Predators include: - blue crab - oyster drills - horseshoe crabs - cow-nosed rays - herring gulls - waterfowl - bottom feeding fish - commercial and recreational fisheries.	
Adult	Tolerate salinity 3-35 ppt. Optimum 16-32 ppt. Clams occur on shallow subtidal beds in stable substrates at depths less than 6-10 m.	Suspension feeder - phytoplankton - microzooplankton - bacteria - detritus	Clams reach sexual maturity in one year. Growth is influenced by water currents, food supply, temperature, and sediment type.	Adults occur in deep, permanent burrows in shallow water.		

TABLE 1r. ENVIRONMENTAL TOLERANCES OF PERCA FLAVESCENS (YELLOW PERCH) EAST COAST RANGE OF NOVA SCOTIA TO SOUTH CAROLINA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Egg	0-0.5 ppt salinity. Non-tidal and tidal-fresh water.	Not applicable	Low temperatures during spawning season cause an extended incubation period (2-3 wks); larvae more developed at hatch than other anadromous species.	Not applicable	No information	Setzler et al. 1980 Lippson et al. 1979 Auld and Schubel 1974 Daiber et al. 1976 Muncy 1962
Larvae	Tolerate salinity 0-2 ppt. Optimum 0-0.5 ppt. Shallow, freshwater; survival reduced when sediment concentrations exceed 500 mg L^{-1}.	- plankton	Salinities greater than 2 ppt interfere with larval development.	Larvae move downstream after hatching; concentrate near surface, form schools.	Preyed upon by white perch, striped bass, chain pickerel.	
Juvenile	0.5-10 ppt, concentrate at salinities of 5-7 ppt in summer. Found in vegetated areas near shore.	- small crustaceans - insects - worms - molluscs	Grows quickly during first year; growth rate decreases with age. Females have greater growth rate than males.	Initially concentrate at surface, become demersal at about 25 mm.	Preyed upon by fish such as white perch and striped bass, birds, mammals. Compete with white perch and striped bass.	
Adult	Tolerate 0-13 ppt salinity, prefer 5-7 ppt in summer. Prefer higher salinity, tidal waters with muddy substrate.	- bay anchovies - silversides - minnows - isopods - amphipods - snails - crustaceans	Males mature at 1 year of age, females mature at age 2 or 3; grow to 53 cm. Large populations cause stunting of adults.	Spring migration upstream to spawn; return downstream after spawning.	Competes with smaller fish and invertebrates for food. Preyed upon by birds (mergansers), fish (gars and pikes), and man.	

TABLE 1a. LIFE HISTORY OF *POMATOMUS SALTATRIX* (BLUEFISH) NOVA SCOTIA TO ARGENTINA

LIFE STAGE	HABITAT REQUIREMENTS	FOOD AND FEEDING FACTORS	GROWTH & DEVELOPMENT FACTORS	BEHAVIOR	PREDATORS AND COMPETITORS	SELECTED REFERENCES
Eggs	Eggs released off-shore in two distinct waves; spring spawning occurs in the Gulf Stream, while summer spawning occurs over the continental shelf.	Not applicable	No information	Not applicable	No information	Lippson et al. 1979 Hildebrand and Schroeder 1928 Jones et al. 1978 Daiber et al. 1976
Larvae	No information	No information	No information	No information	No information	
Juvenile	0-37.5 ppt salinity. The larger the juvenile population, the greater the penetration into the Bay.	- copepods - molluscs - planktivorous crustaceans - any fish smaller than themselves	Juveniles grow quickly during the first summer.	Juveniles from spring spawning enter the Bay in early summer; leave the Bay by late fall, heading offshore and southward.	No information	
Adult	7-34 ppt salinity. Both sexually mature and immature adults enter the Bay; the larger the adult population, the greater the penetration into the Bay.	Voracious predator - menhaden - silversides - bay anchovy - herring spp. - crustaceans - annelids	Bluefish are sexually mature at about 30.0 cm, and reach a maximum length of 93.4 cm.	Bluefish, a marine species, enters the Bay in spring and summer to feed. Schools of bluefish move seasonally in relation to food abundance.	Compete with other top predators such as striped bass. Target of a commercial and recreational fishery.	

APPENDIX C

SUBMERGED AQUATIC VEGETATION

Compiled from Stevenson and Confer 1978.

APPENDIX C

SUBMERGED AQUATIC VEGETATION

Ceratophyllum demersum (Coontail)

Characea: Chara, Nitella, Toypellas

Elodea canadensis (Common elodea)

Myriophyllum spicatum (Eurasian watermilfoil)

Najas guadalupensis (Bushy pondweed)

Potamogeton pectinatus (Sago pondweed)

Potamogeton perfoliatus (Redhead grass)

Ruppia maritima (Widgeongrass)

Vallisneria americana (Wild celery)

Zannichellia palustris (Horned pondweed)

Zostera marina (Eelgrass)

Ceratophyllum demersum (Coontail)

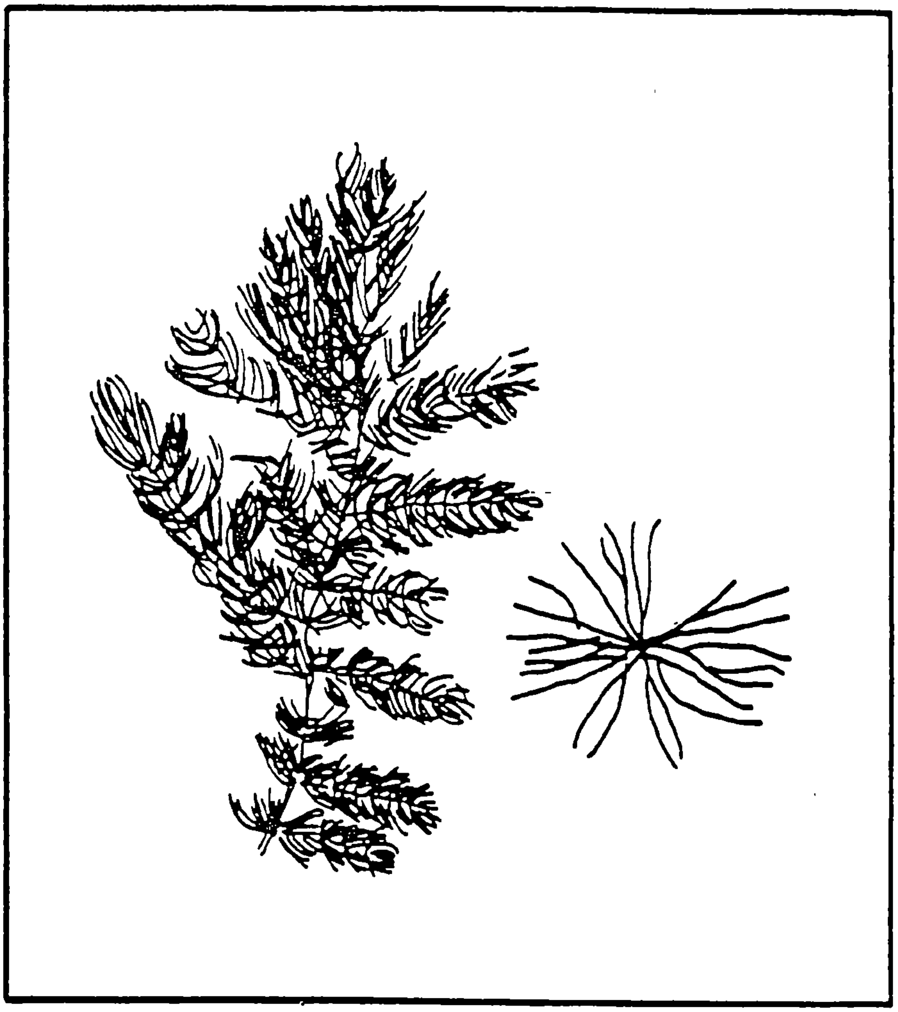
	References
Distribution	
Frequents quiet, freshwater pools and slow streams. Also in the Maryland portion of the Chesapeake Bay.	Mason 1969
Temperature	
Critical minimum temperature for vegetative growth of 20°C, with optimum growth at 30°C.	Wilkinson 1963
Salinity	
Essentially freshwater, but grows normally in salinities under 6.5°/₀₀.	Bourn 1932
Substrate	
Often grows independently of substrate material.	Sculthorpe 1967
Light, Depth and Turbidity	
Shade tolerant, requiring a minimum of 2 percent full sunlight for optimum growth. Not considered to be depth limited due to its rootless nature. Turbidity is not as detrimental for coontail as for rooted vegetation because of shade tolerance and water surface habitat.	Chapman et al. 1974

Ceratophyllum demersum (Coontail)
Continued

References

Consumer Utilization

Foliage and seeds rated as having great importance to ducks, coots, geese, grebes, swans, waders, shore and game birds. Moderate importance as fish food, shade, shelter and spawning medium.	Sculthorpe 1967



(copied from Hotchkiss 1967)

Figure 1. Coontail (Ceratophyllum demersum)

Characea: Chara, Nitella, Tolypellas

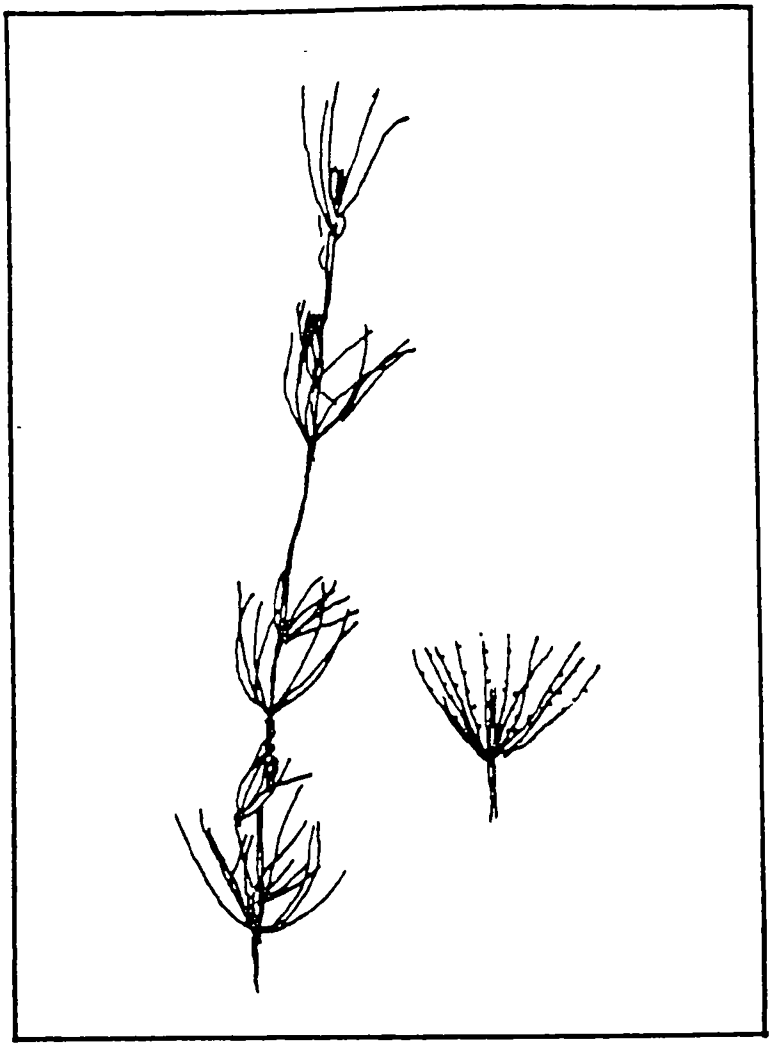
	References
Distribution	
Primarily found in freshwater environments. Some species inhabit brackish waters but are not found in truly marine environments. Found in temperate and tropical regions of all the continents.	Hutchinson 1975 Cook et al. 1974
Temperature	
Germination of Characea occurs after maintenance at 40°C for one to three months.	Hutchinson 1975
Salinity	
Certain species ranged in salinities up to 15°/₀₀ with growth cessation and limited survival at 20°/₀₀.	Dawson 1966
Substrate	
Most species of Characea grow in silt or mud substrate though a small number of species tend to grow in shallow water on sandy bottoms.	Hutchinson 1975
Light, Depth and Turbidity	
The Characea are capable of surviving in low light intensities. Have been found inhabiting fresh water at depths up to 65.5 m (Lake Tahoe), with incident	Hutchinson 1975

References

radiation of slightly more than 2 percent of that reaching the lake surface.

Consumer Utilization

Consumed by many kinds of ducks, especially diving ducks. Also provides habitat for aquatic fauna.	Martin and Uhler 1939



(copied from Hotchkiss 1967)

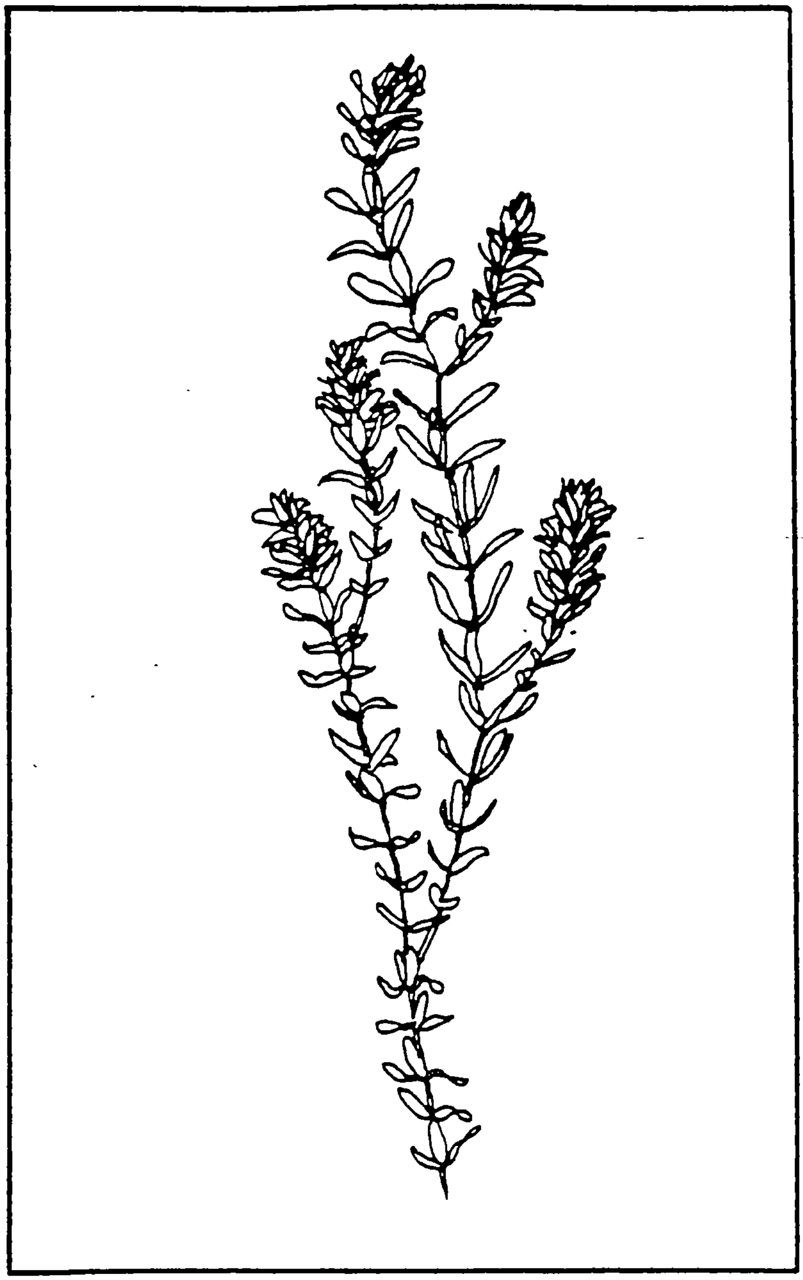
Figure 2. Muskgrass (Chara sp.)

Elodea canadensis (Common elodea)

	References
Distribution	
Endemic to North America and naturalized to many industrialized nations of Europe and the southern hemisphere.	
Temperature	
Water temperatures of 15 to 18°C are necessary for successful growth.	Yeo 1965*b*
Salinity	
Salinity range of fresh water to brackish water of 10°/₀₀.	U.S. Army Corps of Engineers 1974
Substrate	
Prefers a soil to sand substrate. Grows better when rooted than when suspended.	Yeo 1965*b* Hutchinson 1975
Light, Depth and Turbidity	
Maximum frequency of elodea is between 3.0 m and 7.5 m depth. Capable of quickly growing up through covering layers of silt.	Hutchinson 1975

Elodea canadensis (Common elodea)
Continued

	References
Consumer Utilization	
Has little value to water fowl. Generally unpalatable to aquatic insects. Epiphytes grow abundantly between the teeth on the leaf margins and on the upper leaf surfaces.	Martin and Uhler 1939 Hutchinson 1975



(copied from Hotchkiss 1967)

Figure 3. Common elodea (Elodea canadensis)

Myriophyllum spicatum (Eurasian watermilfoil)

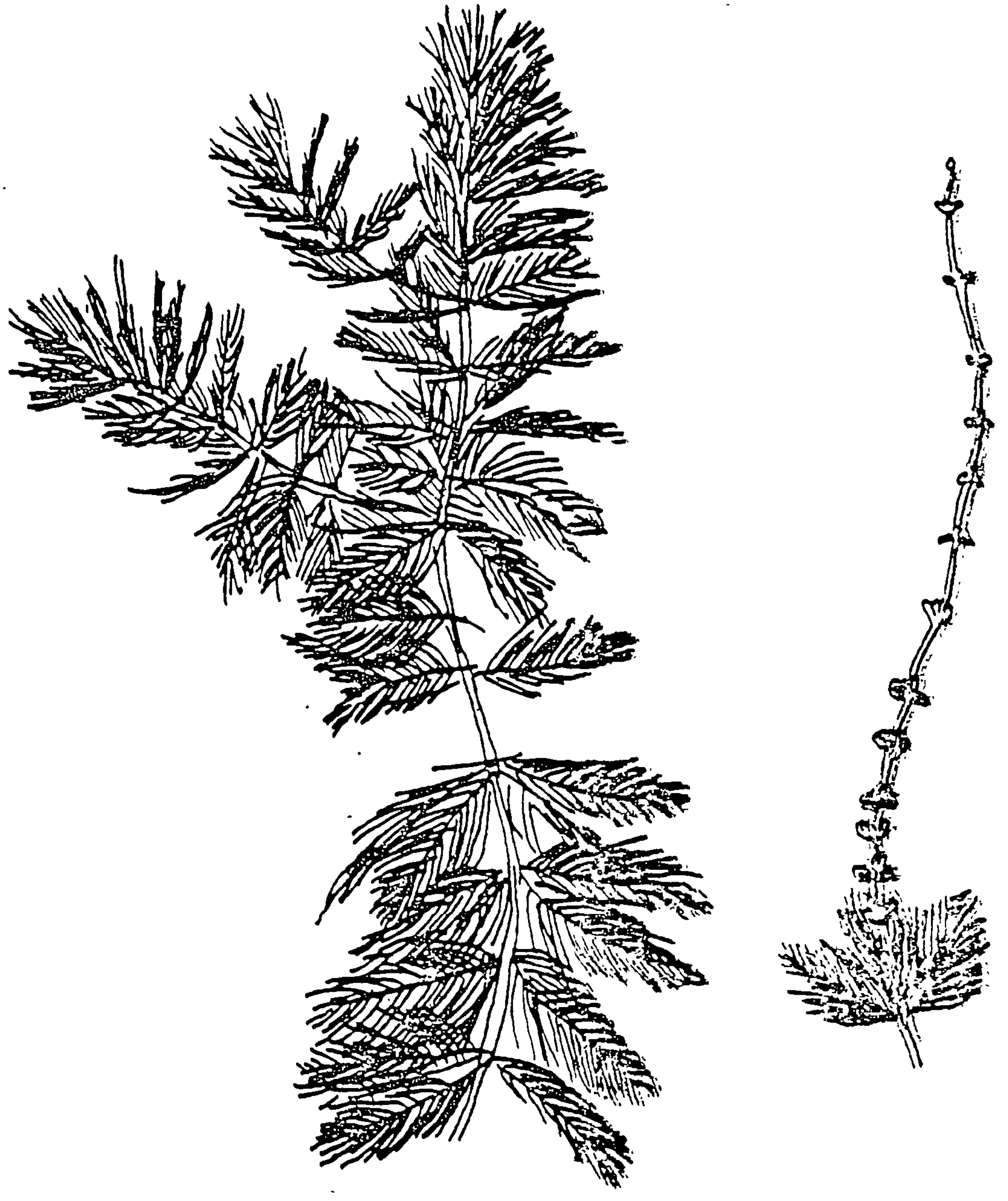
	References
Distribution	
Native to Europe and Asia, is widespread in Europe, Asia and parts of Africa. Found in Chesapeake Bay area, also infested many lakes in New York, New Jersey and Tennessee.	Anonymous 1976 Springer 1959 Springer et al. 1961 Stotts 1961
Temperature	
Found growing in temperatures ranging from 0.1° to 30°C.	Anderson 1964 Anderson et al. 1965
Salinity	
Found in salinities ranging from 0 to 20‰. Grows best in salinities of 0 to 5 ‰. Inhibition starts at 10‰ and becomes severe from 15 to 20‰.	Rawls 1964 Boyer 1960
Substrate	
Grows best in soft muck or sandy muck bottoms. Maximum density coincides with fine organic ooze while minimum density is found in sand.	Patten 1956 Anderson 1972 Steenis et al. 1967 Philipp and Brown 1965 Springer 1959
Light, Depth and Turbidity	
Sensitive to turbidity and grows in water more than 2 m deep, if clear. Limited to 1.5 m in extremely turbid waters.	Southwick 1972 Titus et al. 1975

References

Consumer Utilization

Low grade duck food. Found in digestive tracts of 27 Canada Geese, 6 species of dabbling ducks, 4 species of divers and 31 coots in the vicinity of Back Bay and Currituck Sound. Offers support for aufwuchs which later become food for higher life forms. Crowds out more desirable foods.

Florschutz 1973
Martin et al. 1951
Springer 1959
Springer et al. 1961

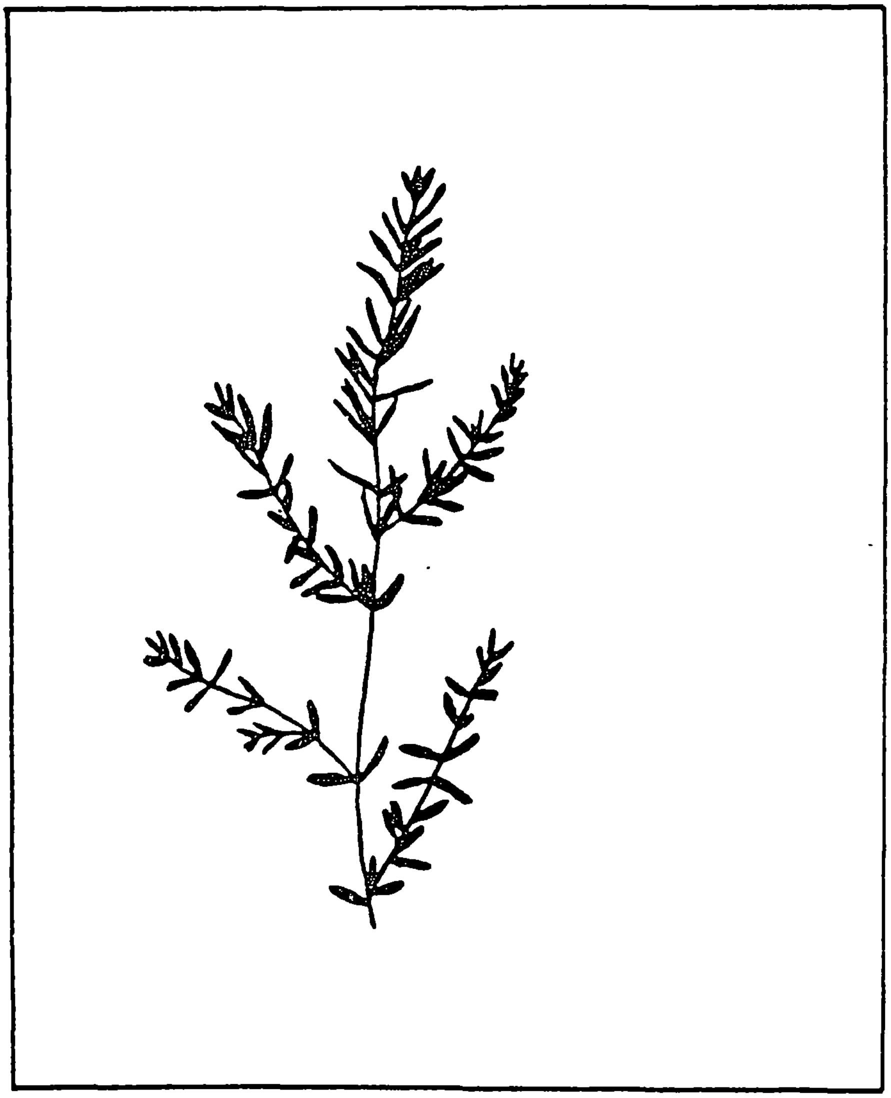


(copied from Hotchkiss 1967)

Figure 4. Eurasian watermilfoil (*Myriophyllum spicatum*)

Najas guadalupenses (Bushy pondweed)

	References
Distribution	
Essentially freshwater or brackish water species, ranging from Oregon to Quebec, and California to Florida.	Hotchkiss 1967 Martin and Uhler 1939
Temperature	
No information	
Salinity	
Prefers 3°/oo salinity. Found in Potomac River at salinities of 6 to 9°/oo.	Steenis 1970
Substrate	
Prefers soils containing a predominance of sand, but tolerates substrate of pure muck.	USDI 1944 Martin and Uhler 1939
Light, Depth and Turbidity	
Usually found in depths ranging from 0.3 to 1.2 m, but has been recorded at depths over 6 m.	Martin and Uhler 1939
Consumer Utilization	
Excellent in food value for waterfowl. Birds eat both the seeds and the leafy plant parts.	Martin and Uhler 1939



(redrawn after Hotchkiss 1967)

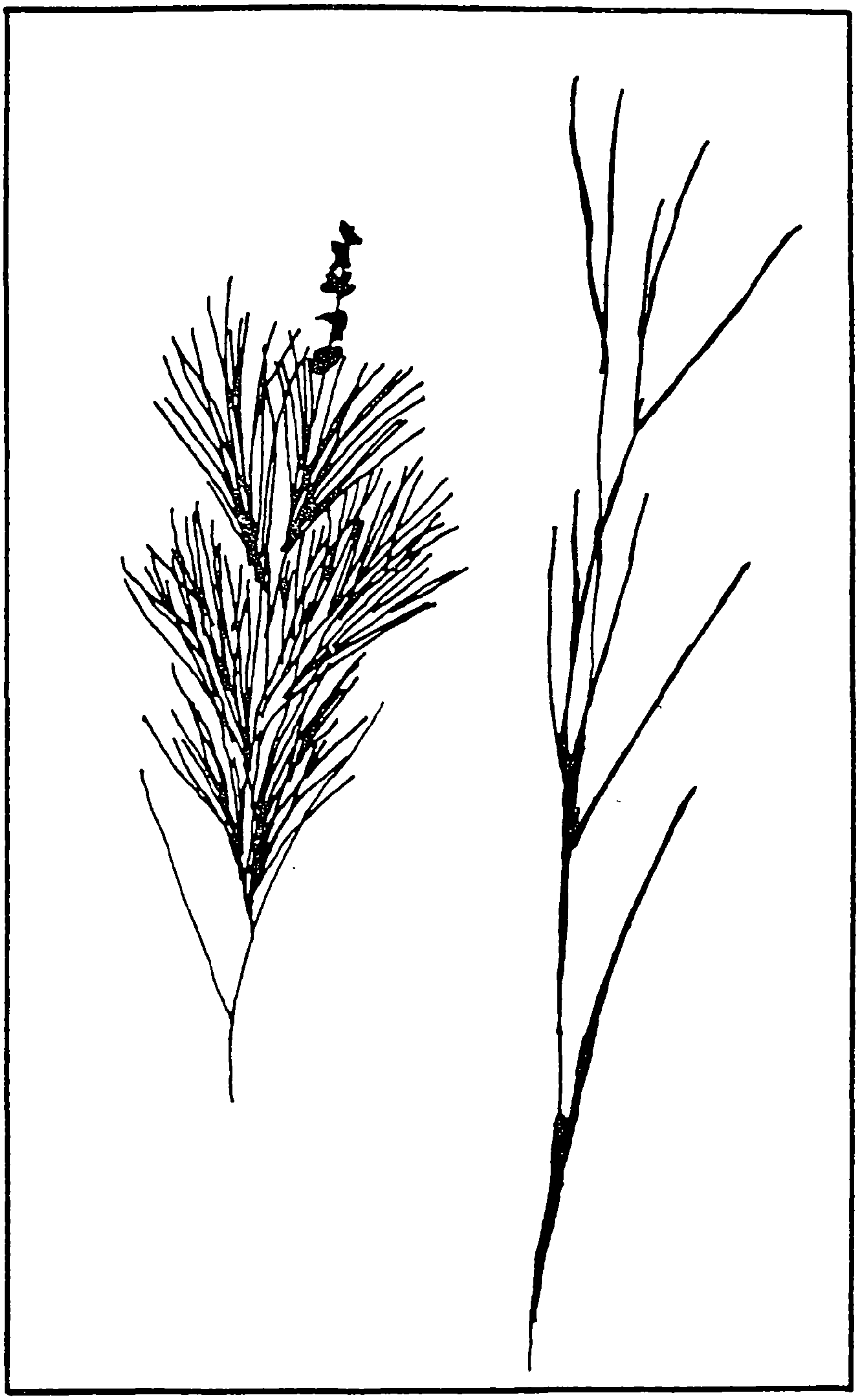
Figure 5. Naiad (Najas sp.)

Potamogeton pectinatus (Sago pondweed)

	References
Distribution	
Range includes freshwater streams and ponds, also brackish coastal waters of the United States and portions of Canada. Most abundant in the northwestern states and the Chesapeake Bay in the United States. Reported to be a pest species of irrigation systems in the west, and in cranberry bogs of Massachusetts.	Martin and Uhler 1939 Hodgeson and Otto 1963 Devlin 1973
Temperature	
Germination shown to occur when water temperature reaches 15 to 18°C.	Yeo 1965*b*
Salinity	
Maximum seed production, seed germination and vegetative growth occurs in freshwater. Salinities of 8 to 9°/₀₀ generally decreased growth and germination rates by 50 percent.	Teeter 1965
Substrate	
Grows on both mud and sand bottoms. Prefers silty bottoms.	Sculthorpe 1967 Rickett 1923
Light, Depth and Turbidity	
Requires at least 3.5 percent total sunlight for growth. Shading produces yellowed, sparse foliage, elongated nodes and rigid unbranched stems.	Bourn 1932

Potamogeton pectinatus (Sago pondweed)
Continued

Consumer Utilization	References
One of the more important waterfowl plant foods. Nutlets and tubers reported to be excellent food source for ducks; rootstocks and stems are consumed to a lesser degree. Also provides protective habitat for fish, oysters, and benthic creatures.	Martin and Uhler 1939 Fassett 1960



(copied from Hotchkiss 1967)

Figure 6. Sago pondweed (Potamogeton pectinatus)

Potamogeton perfoliatus (Redhead grass)

References

Distribution

Fresh and moderately brackish waters. It has been found in Labrador, Quebec, New Brunswick and extends to Eurasia, northern Africa and Australia. Its presence has been recorded in the Chesapeake Bay through 1976.

Ogden 1943
USFWS Migratory Bird and Habitat Research Laboratory 1976

Temperature

Experiments showed that respiration and O_2 consumption increased as temperatures increased from 25 to 40°C, with death occurring at 45°C.

Anderson 1969

Salinity

1.5 to 19°/₀₀, tolerant to 25°/₀₀.

Anderson 1969

Substrate

Grows best on a mixture of organic material and silt with a minimum carbon to nitrogen ratio, a high capacity to recycle ammonia and a low redox potential. Moderately organic muds fairly rich in nitrogen and exchangeable calcium are more suitable than highly organic muds.

Misra 1938

	References
Light, Depth and Turbidity	
Usually found in still or standing water ranging from 0.6 to 1.5 m depth. Maximum rate of photosynthesis attained where light intensity was about 1.1 g cal/cm^2.	Felfoldy 1960 Martin and Uhler 1939
Consumer Utilization	
Seeds, rootstocks and portions of the stem are consumed by Black Ducks, Canvasbacks, Redheads, Ringnecks and other duck species. Also eaten by geese, swans, beaver, deer, muskrat. Provides protective cover for various aquatic organisms.	Martin and Uhler 1939 Fassett 1960

(copied from Hotchkiss 1967)

Figure 7. Redhead grass (Potamogeton perfoliatus)

Ruppia maritima (Widgeongrass)

References

Distribution

Inhabits a wide range of shallow, brackish pools, rivers and estuaries along the Atlantic, Gulf and Pacific Coasts. Also occurs in fresh portions of estuaries, alkaline lakes, ponds and streams and in shallow, saline ponds and river deltas of the Great Salt Lake region.

Martin et al. 1951
Radford et al. 1964
Ungar 1974
Chrysler et al. 1910

Temperature

R. maritima appeared to have two growing seasons within the temperature range of 18° to 30°C. Growth ceased outside this range although some fruiting and flowering occurred at temperatures higher than 30°C.

Joanen and Glasgow 1965

Salinity

Tolerant of a broad salinity range, from 5.0 to 40.0°/oo. Tension zone of over 30°/oo. Flowering and seed set occurs in range of tapwater to 28°/oo.

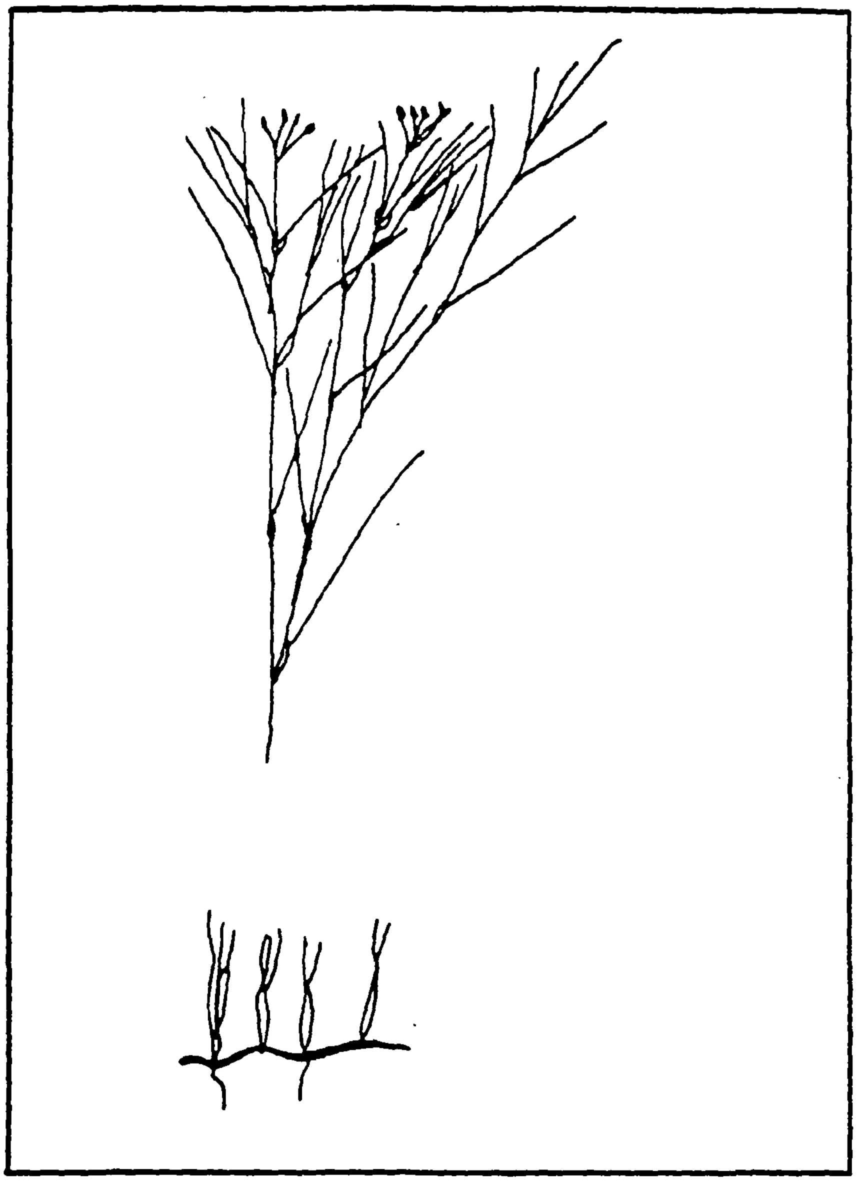
Steenis 1970
Anderson 1972
McMillan 1974

Substrate

Prefers soft bottom muds or sand. Has been found growing on shallow sand shell gravel soils in Russian rivers and streams.

Anderson 1972
Zenkevitch 1963

	References
Light, Depth and Turbidity	
Optimum production in laboratory studies occurred at depth of 60 cm. Is found at depths of a few inches to several feet. Turbidity tolerance less than 25-35 ppm in small ponds; turbidity is especially harmful to young plants prior to the stems reaching the surface.	Joanen and Glasgow 1965
Consumer Utilization	
Serves as food for numerous species of ducks, coots, geese, grebes, swans, marsh and shore birds of the Atlantic, Pacific and Gulf Coasts. Also used as nursery grounds and as a fish spawning medium and cover for marine organisms.	Sculthorpe 1967 Martin and Uhler 1939 Kerwin 1975b



(copied from Hotchkiss 1976)

Figure 8. Widgeongrass (Ruppia maritima)

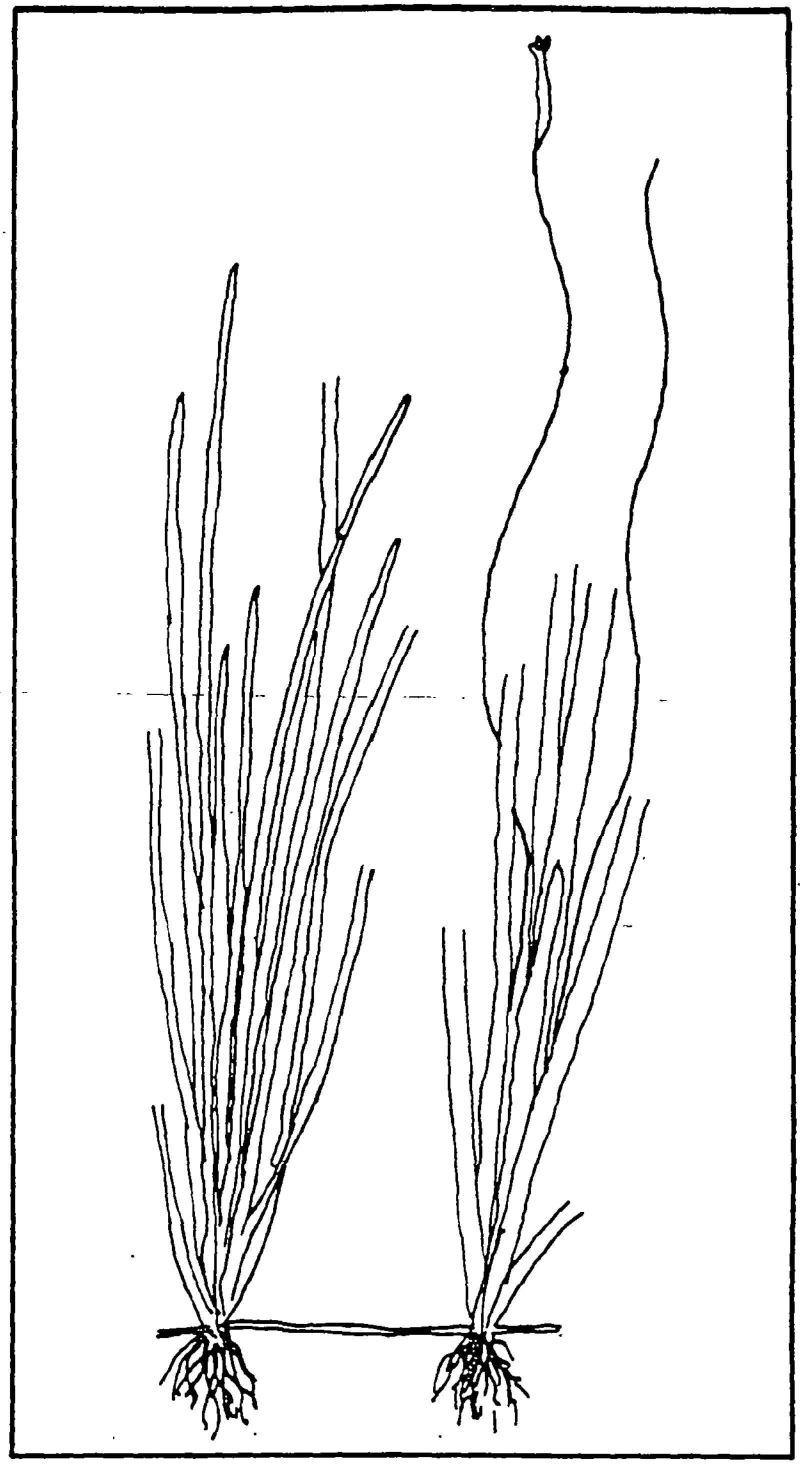
Vallisneria americana (Wildcelery)

	References
Distribution	
Freshwater macrophyte occurring in the tidal streams of the Atlantic Coastal Plain.	Martin and Uhler 1939
Temperature	
Grows best in temperature range of 33 to 36°C. Arrested growth occurs below 19°C.	Wilkinson 1963
Salinity	
Laboratory tests showed that *Vallisneria* could not be maintained in salinities greater than 4.2°/₀₀.	Bourn 1934
Substrate	
Grows equally well in sandy soil and mud. Hutchinson (1975) found that *V. americana* thrived best in a soil of 6.5 percent organics, 8.78 percent gravel, 21.46 percent sand, 47.90 percent silt, 14.26 percent clay.	Schuette and Alder 1927 Hutchinson 1975
Light, Depth and Turbidity	
Able to tolerate muddy, roiled water. Usually found in shallow water (0.5 to 1.0 m).	Steenis 1970

References

Consumer Utilization

All parts of the plant structure are consumed by fish, ducks, coots, geese, grebes, swans, waders, shore and game birds. Also serves as a shade, shelter and spawning medium for fish. — Sculthorpe 1967



(copied from Hotchkiss 1967)

Figure 9. Wildcelery (*Vallisneria americana*)

Zannichellia palustris (Horned pondweed)

References

Distribution

This species has been documented in every state in continental United States; however, it is not a commonly occurring submerged aquatic. Reported occasionally in brackish marshes along the New England coast, rarely found inland. Recorded in Chesapeake Bay and south to Currituck and Pamlico Sound area, North Carolina. — Deane 1910; Fassett 1960

Temperature

In the Chesapeake Bay, the *Zannichellia* populations decline rapidly when temperatures reach 30°C. Reported to exist in temperatures as low as 10.5 to 14.8°C. — Tutin 1940

Salinity

Tolerates freshwater, but prefers brackish waters to 20°/₀₀. — Radford et al. 1964

Substrate

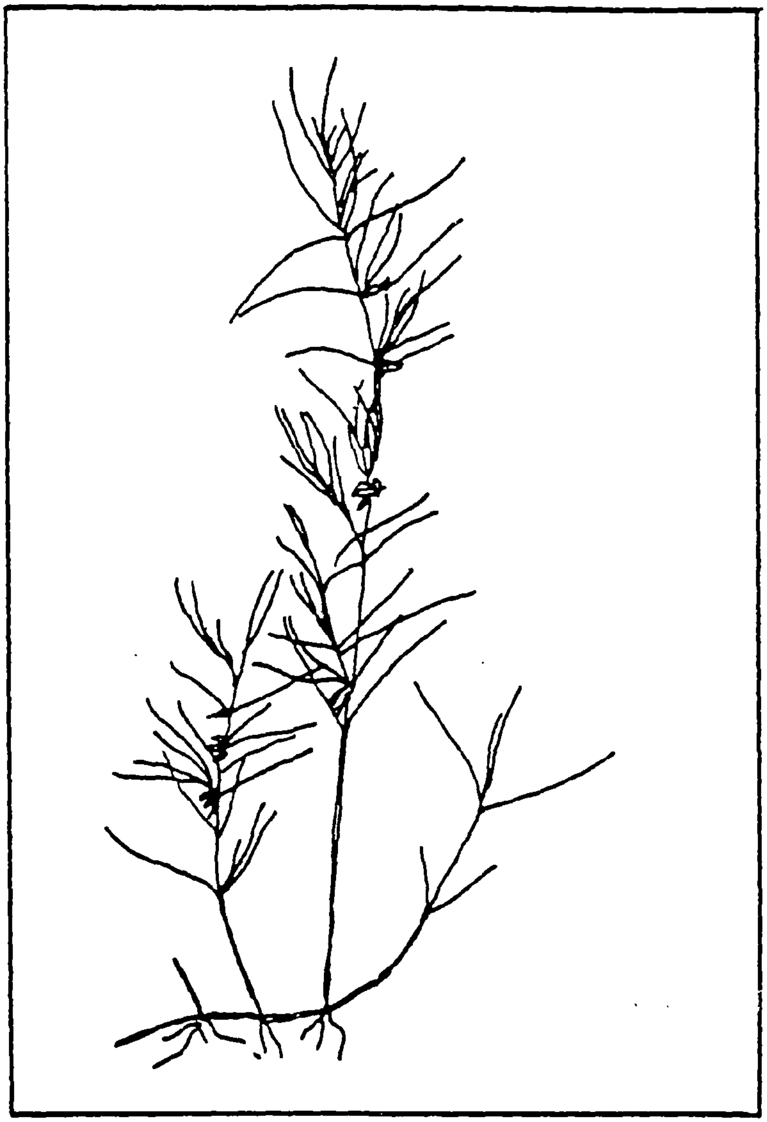
Tends to grow in clay to sandy sediments.

Light, Depth and Turbidity

Prefers shallower water than other submerged aquatics. May need higher light intensities than others; good growth obtained at 4 to 7 percent of the maximum noon summer sunlight. — Correll et al. 1977

Zannichellia palustris (Horned pondweed)
Continued

	References
Consumer Utilization	
Fruits and sometimes foliage are good for waterfowl in brackish pools.	Fassett 1960



(copied from Hotchkiss 1967)

Figure 10. Horned pondweed (Zannichellia palustris)

Zostera marina (Eelgrass)

	References
Distribution	
On the Pacific Coast of North America, eelgrass extends from Grantly Harbor, Alaska, to Agiahampo Lagoon in the Gulf of California. On the Atlantic Coast of North America, eelgrass extends from Hudson Bay, Canada, the southern tip of Greenland, and one locality in Iceland, to Bogue Sound, North Carolina.	McRoy 1968 Steinbeck and Picketts 1941 Cottam 1934b Ostenfeld 1918 Phillips 1974a
Temperature	
Tolerate temperatures from -6°C to 35°C. Photosynthesis decreased sharply above 35°C. Death occurred after exposure to -9°C.	Biebel and McRoy 1971
Salinity	
Can tolerate salinities ranging from 8°/₀₀ to full strength seawater (35°/₀₀).	Phillips 1974a Arasaki 1950a, 1950b Martin and Uhler 1939
Substrate	
Found growing on a wide variety of substrates, from pure firm sand to pure firm mud.	Phillips 1974a

<u>Zostera marina</u> (Eelgrass)
Continued

References

Light, Depth and Turbidity

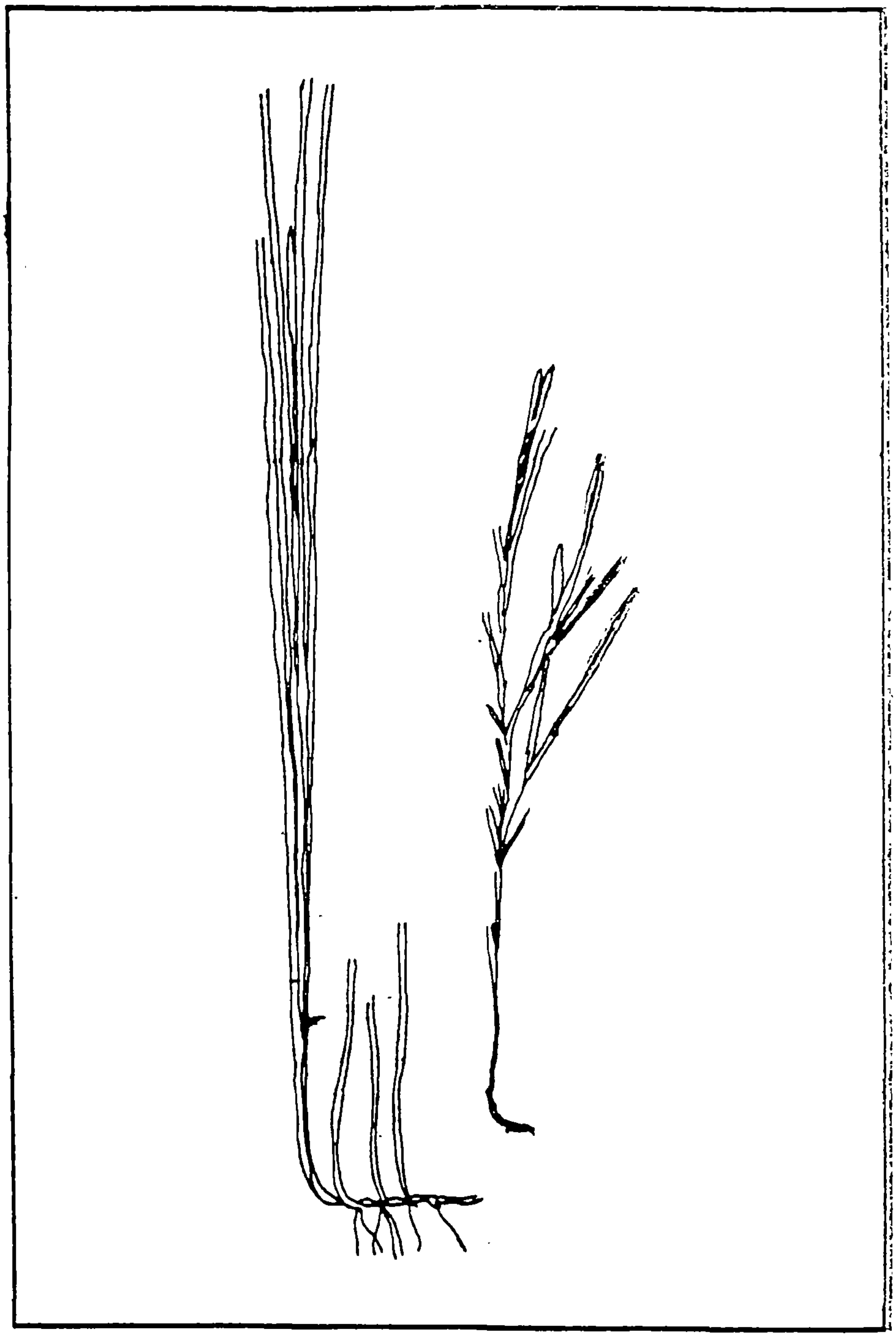
Has been found growing from about 2 m above MLW (minimum low water) to depths down to 30 m. Low light intensity conditions inhibit flowering and turion (young branch) density is decreased in shaded plots.

Cottam and Munro 1954
Phillips 1974a
Backman and Barilotti 1976

Consumer Utilization

The only groups of animals that consume eelgrass directly are waterfowl and sea turtles. Eelgrass beds provide important habitats and nursery areas for many forms of invertebrates and vertebrates, which then serve as food sources of species at higher levels.

Cottam 1934b
Addy and Aylward 1944
Gutsell 1930



(copied from Hotchkiss 1967)

Figure 11. Eelgrass (Zostera marina)

APPENDIX D

Environmental Requirements of certain fish in Gulf of Mexico estuaries

Contents

from Benson 1982

Anchoa hepsetus (striped anchovy)

The distribution of all life stages of striped anchovy appears to be limited primarily by salinity. Christmas and Waller (1973) reported this species in salinities ranging from 5.0 ppt to 3.5 ppt. Perry and Boyes (1978) collected 95.6% of their specimens in salinities between 20 and 30 ppt, largely in waters south of the Gulf Intracoastal Waterway. This fish is most abundant at temperatures ranging from 20° to 30°C (68° to 86°F) (Perry and Boyes 1978).

Anchoa mitchilli (bay anchovy)

Although the distribution of the bay anchovy in Mississippi Sound waters is not greatly affected by differences in salinities, low winter temperatures appear to cause some movement to deeper, warmer offshore waters (Springer and Woodburn 1960; Christmas and Waller 1973). Swingle (1971) found them to be nearly equally distributed in salinities between 5 and 19 ppt in Alabama coastal waters. Highest catches were in salinities ranging from 20.0 to 29.9 ppt. In Mississippi Sound, Christmas and Waller (1973) established no relationships between the distribution of anchovies and salinities above 2 ppt. Perry and Christmas (1973) found larvae in Mississippi waters in salinities ranging from 16.6 to 27.8 ppt. Bay anchovies were taken at temperatures from 5.0° to 34.9°C (41.0° to 94.8°F), but the largest numbers were in water temperatures between 10.0° and 14.9°C (50.0° and 58.8°F) (Christmas and Waller 1973).

Arius felis (sea catfish)

Sea catfish in estuaries in the summer are most abundant in water temperatures from 19° to 25°C (66° to 77°F). Year round, they have been taken in the range of 5.0° to 34.9°C (41.0° to 94.8°F) (Perret et al. 1971; Adkins and Bowman 1976; Drummond and Pellegrin 1977; Johnson 1978). This euryhaline species is common in salinities from 0 to 45 ppt, but some tolerate 60 ppt. A preference of higher salinities has been suggested (Gunter 1947; Johnson 1978; Lee et al. 1980). Breeding occurs in waters having a salinity range of 13 to 30 ppt.

The developmental stage of larvae incubating in the oral cavity may determine the location of the parent male (Harvey 1971). Younger larvae tolerate salinities up to 12.8 ppt, but more developed larvae tolerate salinities of 16.7 to 28.3 ppt (Harvey 1971). Juveniles are most numerous in low salinities (Johnson 1978).

Although minimum dissolved oxygen requirements of sea catfish are not known, this fish sometimes lives in dredged semiclosed and closed canals that are characterized by low oxygen concentrations (Adkins and Bowman 1976). They are found in moderately turbid water (Gunter 1947; Lee et al. 1980).

Sea catfish principally live at depths from 4 to 7 m (13 to 23 ft), but may occupy waters as deep as 36 m (118 ft) (Lee 1937; Johnson 1978). Major substrates are muddy or sandy bottoms rich in nutrients (Etchevers 1978; Shipp 1981).

Paralichthys lethostigma (southern flounder)

The southern flounder is euryhaline, occurring in waters with salinities from 0 to 60 ppt. The normal range is from about 10 to 31 ppt. They live at water temperatures from 9.9° to 30.5°C (49.8° to 86.9°F), but are most common between 14.5° and 21.6°C (58.1° and 70.9°F) (Stokes 1973). The temperatures and salinities where southern flounder were collected in Mississippi Sound by Christmas and Waller (1973) ranged from 5.0° to 34.9°C (41.0° to 94.8°F) and 0.0 to 29.9 ppt. The juveniles may live in freshwater for short periods.

Juveniles are usually most abundant in shallow areas with aquatic vegetation (shoal grass and other sea grasses) on a muddy bottom. Adults also tend to favor aquatic vegetation such as Spartina alterniflora. Some flounders overwinter in the deeper holes and channels of estuaries, but most (adults and second-year juveniles) migrate to Gulf waters in the fall (Gunter 1945).

Mugil cephalus (striped mullet)

Striped mullet live in freshwater and in salinities up to 75 ppt. In Texas estuaries the mullet were about equally distributed in water of all salinities (Gunter 1945). They have been taken in Mississippi in salinities ranging from 0.0 to 35.5 ppt (Christmas and Waller 1973).

Fish less than 3.6 cm (1.4 inches) long are most abundant in salinities from 0.0 to 14.9 ppt. Juveniles (up to 7.9 cm or 3.1 inches long) prefer lower salinities and warmer waters than larger fish. Juveniles are mostly taken in salinities from 0 to 10 ppt when temperatures range from 25° to 30°C (77° to 86°F). Fish up to 11 cm (4 inches) long are abundant at salinities from 0 to 20 ppt at temperatures of 7° to 30°C (45° to 86°F) (Etzold and Christmas 1979). Highest catches in samples from Mississippi Sound were in the range of 7° to 20°C (45° to 68°F). Mullet are often killed in water temperatures less than 5°C (41°F) (J.C. Parker 1971), and they tend to aggregate in sheltered areas before the arrival of cold weather.

Pomatomus saltatrix (bluefish)

Temperature and salinity are the only factors cited by Wilk (1977) as determinants of the distribution of bluefish on the Atlantic coast. Extensive data from egg and larval collections on the outer continental shelf of Virginia showed that maximum spawning occurred at 25.6°C (78.1°F) with none below 18°C (64°F) (Norcross et al. 1974). Minimum spawning temperature is about 14°C (57°F) (Hardy 1978). Bluefish seem to prefer salinities from 26.6 to 34.9 ppt. Limited larvae collections in the Gulf of Mexico were found in a temperature range of 23.2° to 26.4°C (73.8° to 79.6°F) and a surface salinity range of 35.7 to 36.6 ppt (Barger et al. 1978). In estuaries they rarely live in salinities below 10 ppt. Hardy (1978) suggested 7 ppt as the minimum salinity. Lacking are data on the effects of substrate, turbidity, tides, or dissolved oxygen on bluefish distribution. Bluefish activity patterns are highly oriented to vision (Olla and Studholme 1979), however, and bluefish are not likely to frequent turbid areas.

Pogonias cromis (black drum)

Black drum are euryhaline during all life stages, i.e., they occur in salinities from 0 to 35 ppt. The species is most common at salinities ranging from 9 to 26 ppt (Gunter 1956; Etzold and Christmas 1979), but some inhabit water with salinities as high as 80 ppt. The black drum is usually taken at water temperatures from 12° to 30°C (54° to 86°F). This fish inhabits areas with sand or soft bottoms as well as brackish marshes and oyster reefs (Etzold and Christmas 1979). The preferred habitat of juveniles during the first 3 months are muddy, nutrient-rich, marsh habitats such as tidal creeks.

Sciaenops ocellatus (red drum)

The general salinity range for red drum is 0 to 30 ppt, but some tolerate salinities up to 50 ppt (Theiling and Loyacano 1976). Larvae and juveniles were taken at salinities between 5.0 and 35.5 ppt in one study (Christmas and Waller 1973), but most occur at salinities from 9 to 26 ppt. The larger fish seem to prefer higher salinities. Red drum are most abundant in salinities from 20 to 25 ppt (Etzold and Christmas 1979), and from 25 to 30 ppt (Kilby 1955). Overall, red drum prefer moderate to high salinities.

Red drum have been observed in water temperatures ranging from 2° to 29°C (36° to 84°F). Some young fish were found in a temperature range of 20.5° to 31°C (68.9° to 87.8°F). The highest catches were at temperatures between 20° and 25°C (68° and 77°F) (Etzold and Christmas 1979). Large numbers of red drum have been reported killed in severe cold spells (Adkins et al. 1979).

Red drum thrive in waters over sand, mud, or sandy mud bottoms and occasionally in and among aquatic vegetation.