THE BIOLOGY OF THE ESTUARY[1]

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An estuary is a mixture of a river and the sea. More exactly, it is a semi-enclosed body of water which has a free connection with the open sea and within which sea water is measurably diluted by fresh water from land drainage.[2] Each estuary is a site of vigorous interaction among land, sea and air. The symposium cover shows a diagram of one principal type, the drowned valley or coastal plain estuary which is found in many coastal areas.

There is enormous variation among the nearly 900 estuaries along the coasts of the United States. The Atlantic Coast includes many of them; among these, the Chesapeake and Delaware Bays (Fig. 1) are large and excellent examples of drowned valleys and have received much research attention. Such coastal plain estuaries are the prototypes for most of the characteristics and examples presented in this discussion.

Other types of estuaries, and those in regions other than the Atlantic Coast, differ from this summary to varying degrees. It is not possible or appropriate to reduce all estuaries to a single characterization. Each, in reality, is an individual ecosystem with its own interesting identity, reflecting the highly local effects of river, sea, land and air.

Glacier-gouged fjords, such as occur in Norway and the Pacific Northwest, are

[1]Contribution No. 421 from the Chesapeake Biological Laboratory. The Senior author is Director of the Laboratory and the second author is a Research Associate.

[2]Definition of Dr. Donald W. Pritchard.

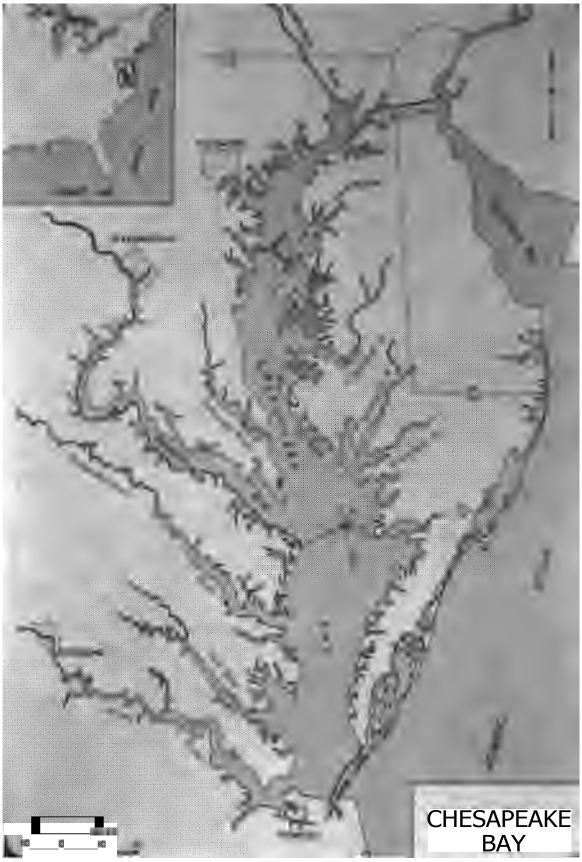


Figure 1

one kind of estuary (Fig. 2). Earthquakes, land shifts and other violent actions created estuaries such as San Francisco Bay. Barrier beaches have slowly developed to enclose Biscayne Bay in Florida and the lagoon behind Ocean City, Maryland (Fig. 3), and scores of comparable coastal lagoons, especially along the Gulf Coast. Some estuaries contain a mixture of oceanic and land-sourced water but are not easily classified, such as the area in Florida around Ten Thousand Islands and at Cape Sable.

SOME PHYSICAL, CHEMICAL AND GEOLOGICAL CHARACTERISTICS

There are, however, characteristics which appear to be common to many estuaries. As shown by a section along the center of a simplified model (Fig. 4),

Figure 2

Figure 3

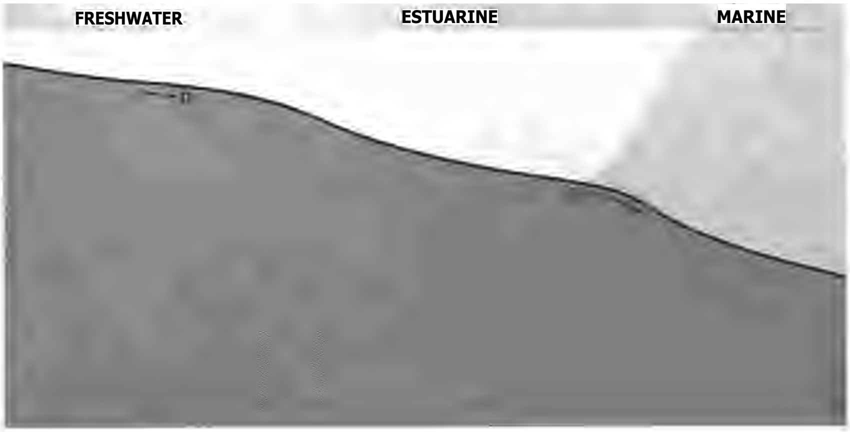


Figure 4

Courtesy U.S. Army Corps of Engineers

Figure 5

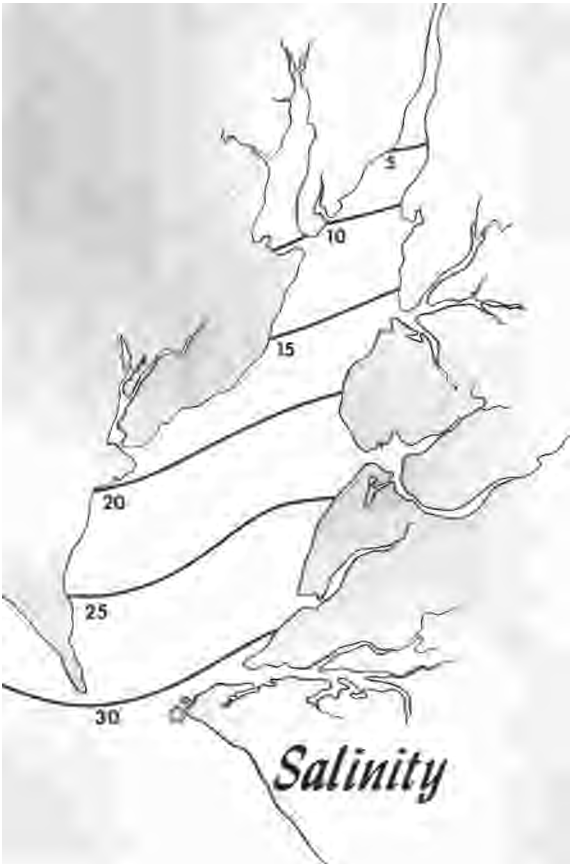


Figure 6

there is fresh water at the river end, oceanic conditions at the other, with the mixing system called the estuary located between. The river influence may originate far inland, and the oceanic influence may derive far beyond the continental shelf Fig. 5 or the edge of the open sea.

In most estuaries, there is a gradient in salt content from high values of 30 to 35 parts of salt per thousand parts of water at the ocean end to zero salinity at the river end. Isohaline lines following the same salinity value, however, do not usually run straight across the estuary. The earth's rotation causes these lines to be higher on the right-hand side facing upstream in the northern hemisphere Fig. 6 and on the left-hand side in the southern hemisphere. Sampling also reveals that deeper waters are usually saltier than surface waters and that the ebb

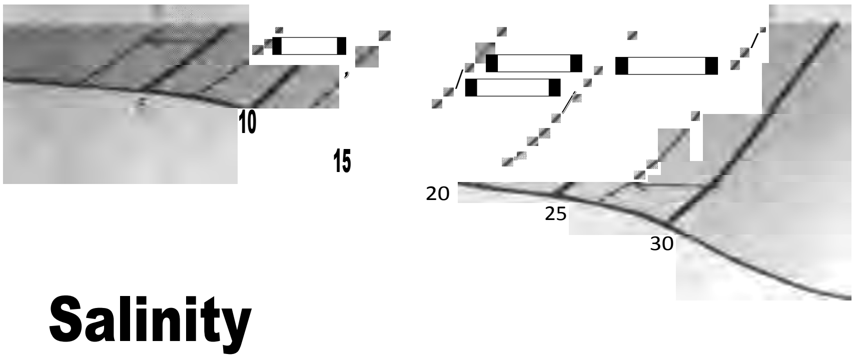


Figure 7

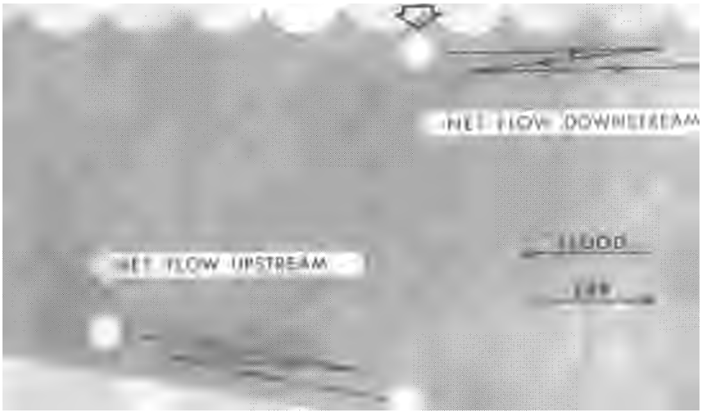
and flow of the tide carry the isohalines up and down the estuary (Fig. 7). These lines of uniform salt content are also driven downstream when the river flow is high and upstream during the periods of low flow from the land. Since high-flow runoff is often several hundred times as great as low-flow runoff, seasonal salinity variation may be very large at one location.

Many of the coastal plain estuaries contain a two-layered system of circulation which is of unique importance to the species which live there. This circulation pattern is the result of the intrusion of heavier salt water from the ocean under less saline and lighter water from the river. Particles of water near the surface undergo a net downstream movement, whereas water particles near the bottom are carried toward the upper end of the system (Fig. 8). This creates a stratified system, with a distinctive estuarine pattern of circulation (Fig. 9) that results in transportation of organisms in the surface water toward the sea and of organisms in the bottom water toward the river.

The total quantity of water flowing past each point of land increases enormously toward the ocean. In a diagrammatic representation to suggest the increase, 1R can equal the flow from the river and the quantity at various locations may be shown in multiples of R (Fig. 10). It is clear that far greater volumes of river water are available for dilution of wastes (if that is desired) in the seaward portion of the estuary.

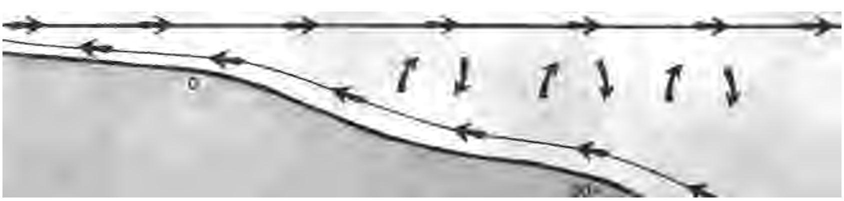
River water contains sediments which are washed down from the river or eroded from the shore. The constant input of this solid material eventually fills

START



START

Figure 8



Circulation

Figure 9

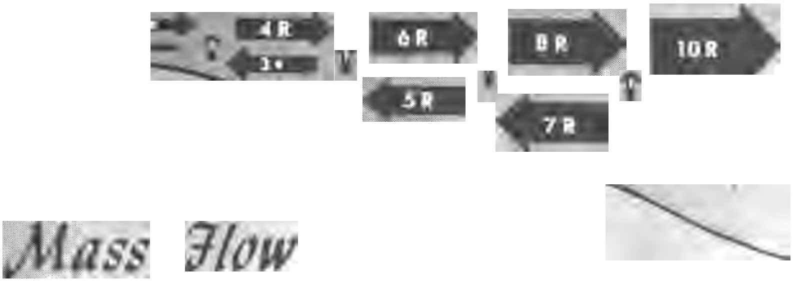


Figure 10

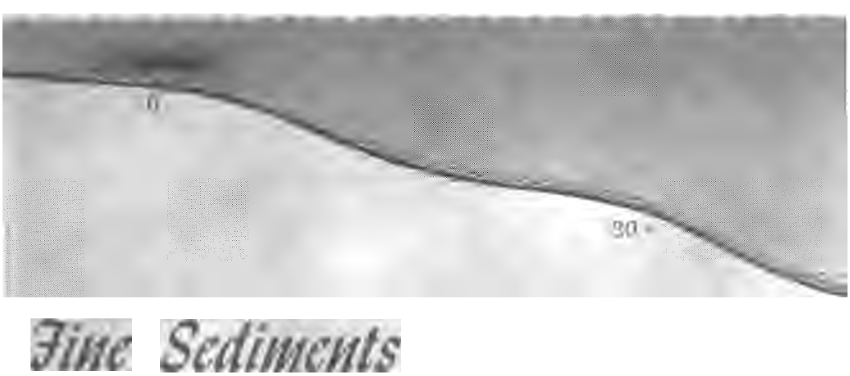


Figure 11

Figure 12

each basin or builds a delta out into the sea. In large estuaries, the highest concentration of suspended sediment is usually found in the low salinity portion (Fig. 11). This is where flocculation occurs, where the broadening of the bay permits sediment to settle, and where currents from wind and waves frequently resuspend and redistribute sediments. Permanent accumulation occurs in the deeper channels (Fig. 12), where compact deposits of fine particles may be over a hundred feet deep. The sediments absorb many chemicals and remove them from the water unless dredging or stirring releases them or biological activity removes the chemicals from the deposit.

Physically, estuaries are influenced principally by variations in river flow, density differences between water masses, tidal movements, the physical shape of the basin, the earth's rotation, and friction. Because they are relatively shallow, estuaries are more affected than the open sea by wind, changes in air temperature, and sunlight. Man's effects on the physical parameters are rapidly increasing. Flow rates, temperatures and vertical stratification all change seasonally; also, there are short-term variations in all physical conditions.

The chemical composition of estuarine water at one site is usually the quantitative resultant of the mixture of seawater (with stable inorganic ratios and more variable organic components) with land-sourced water (chemically related to the river basin). The form and chemical activity of elements and compounds in estuaries are only partially understood. Chemicals may enter physical association with the abundant silts and microorganisms, interact chemically with the great variety of other elements and compounds present, or enter the biochemical processes of the diverse biota. Addition of such substances as nutrient salts from treated sewage, trace metals or other compounds from industrial waste, pesticides, or other materials from specific points of origin, will produce patterns which are not the simple resultants of admixture of ocean and river water.

All of these geological, physical, and chemical patterns create the environment of the living organisms which are so frequently abundant in estuaries. They produce a dynamic, variable, and highly stressful environment for life, and they have many important effects on the selection and abundance of successful plant and animal species.

THE BIOLOGICAL PATTERNS

Bacteria are ubiquitous and abundant in estuaries. Many surfaces and the water mass itself are rich in bacterial flora. As "little bags of enzymes" they are important to many chemical cycling and recycling processes. They are also important to the health of estuarine species and people and there is urgent need for increased comprehension of their roles in estuaries.

The only food factories in estuaries, as on the rest of the earth, are plants. They use nutrients and carbon dioxide in the photosynthetic processes to create organic materials. Drifting one-celled or colonial phytoplankton are frequently present in quantities of millions of organisms per liter of water. Measurement of phytoplankton and of its rates of production are not easy; therefore, use is made of indirect techniques such as comparing oxygen production in light and dark bottles placed in stable conditions of temperature and light for fixed periods of time. Such studies show that phytoplankton, in summer, is often most dense near the surface and in the low salinity areas (Fig. 13). In winter, the crop is smaller and more uniformly distributed (Fig. 14), but food production continues.

Planktonic plants are the only important plants in the open sea, but the rooted aquatic plants are of enormous importance in the shallow waters of estuaries at the edge of the land. These form two kinds of communities-

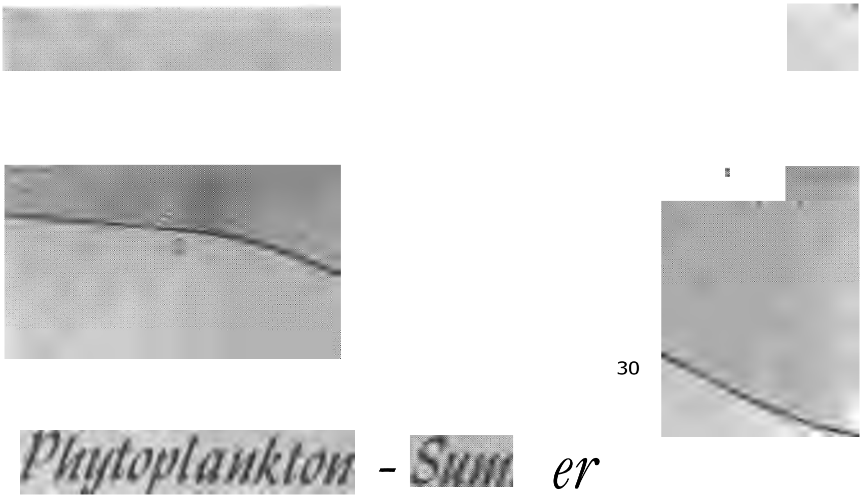


Figure 13

Figure 14

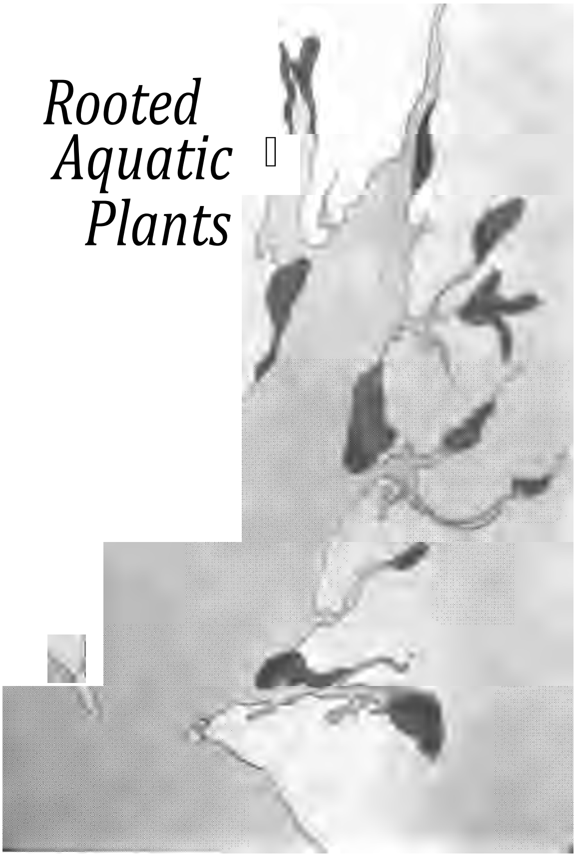


Figure 15

submerged beds and marshes (Fig. 15). Subsurface rooted plants (in which the "root" is more accurately called a hold-fast) capture nutrients which are built into plant tissues during their growing season. These beds are excellent habitats for many fish, crustacea and other species. In temperate climates, these beds die back during fall and winter, releasing organic detritus. Films or beds of algae on the bottom are sometimes highly productive.

Marshlands (Fig. 16) vary, especially in relation to salinity, the available substrate, and longitude. Recent research has helped to clarify their complex and unique roles in coastal systems. Briefly, they are organic factories, traps for sediments, reservoirs for nutrients and other chemicals, and the productive and essential habitat for a large number of invertebrates, fish, reptiles, birds and mammals. Annual plant growth and decay, providing continuing large quantities

Figure 16

of organic detritus, is one of the major components of the cycling of nutrients in estuaries.

A portion of the plant material is consumed by animals. The zooplankton includes abundant copepods, shrimplike species (Fig. 17), larvae of almost all of the animals which live in estuaries (Fig. 18), jellyfishes, and other drifting species. Many of these consume phytoplankton or browse on larger plants, but some ingest detritus, strip off the bacterial film which has developed, and evacuate the detritus to act again as a substrate. Zooplankters, like all other estuarine species, reveal behavioral patterns which permit them to be successful in the specific environment of the estuary. A diurnal migration cycle has been observed in many species (Fig. 19). In the ocean, this would involve only vertical movement. In the water circulation pattern of a two-layered estuary (Fig. 8), however, this vertical movement translates into upbay movement during the day, and downbay transport at night—resulting in a roughly circular motion which retains the species near its optimal salinity range. Other interesting mechanisms are known to exist which prevent zooplankton populations from being washed out to sea, and there are probably undiscovered adaptations which assist the species.

The bottom species, collectively called the benthos, are usually more abundant and valuable in estuaries than in fresh water or the ocean. The species are highly diverse, including many annelid worms, a variety of crustacea, molluscs, and associated fish and invertebrates. Many feed by various filtering

From Sir Alistair Hardy 's The Open Sea—by permission Houghton Mifflin Co., Philadelphia

Figure 17

processes, and this continuous removal of phytoplankters and other food particles is an effective trapping of nutrients flowing through the estuary.

The rich shellfish beds of Chesapeake Bay and many other bays on all coasts are vivid examples of captured food incorporated into sessile and harvestable animals. Shellfish beds are widely dispersed in estuaries, with each species in its own optimal habitat. Oysters of various species are found on all coasts of the United States, but several of the most successful species occur only in estuarine environments. Soft-shell clams are more northern in distribution and range from low to high salinities. Some of the densest clam beds are in the Chesapeake, near the southern edge of their range (Fig. 20). The bottom sediments of many estuarine areas contain a varied and abundant mixture of species which is revealed only by sieving and washing (Fig. 21).

From Nature Adrift by James Fraser

Figure 18

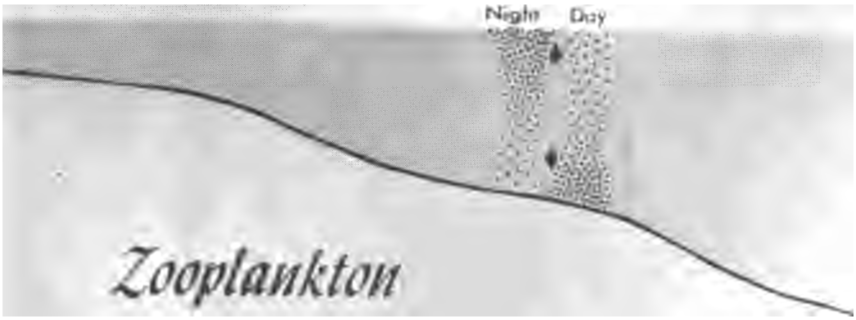


Figure 19

Figure 20

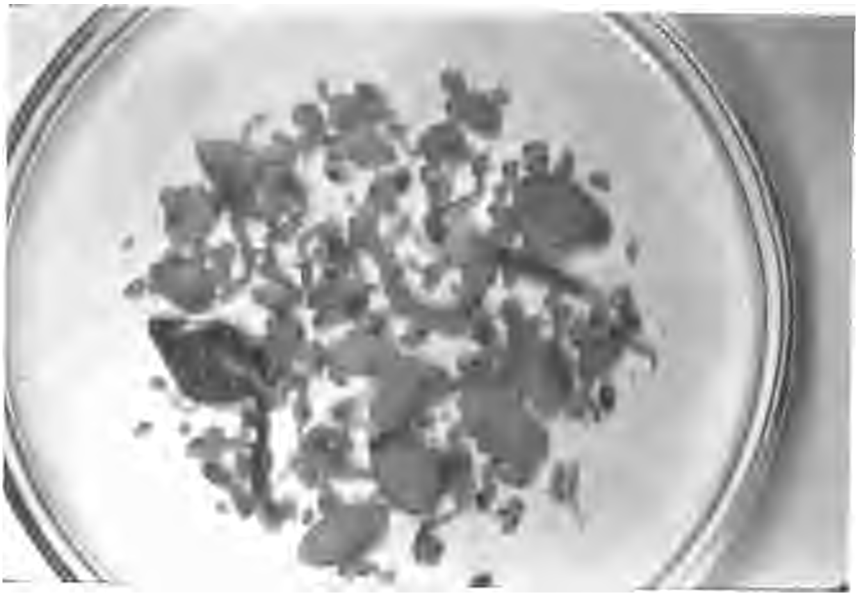


Figure 21

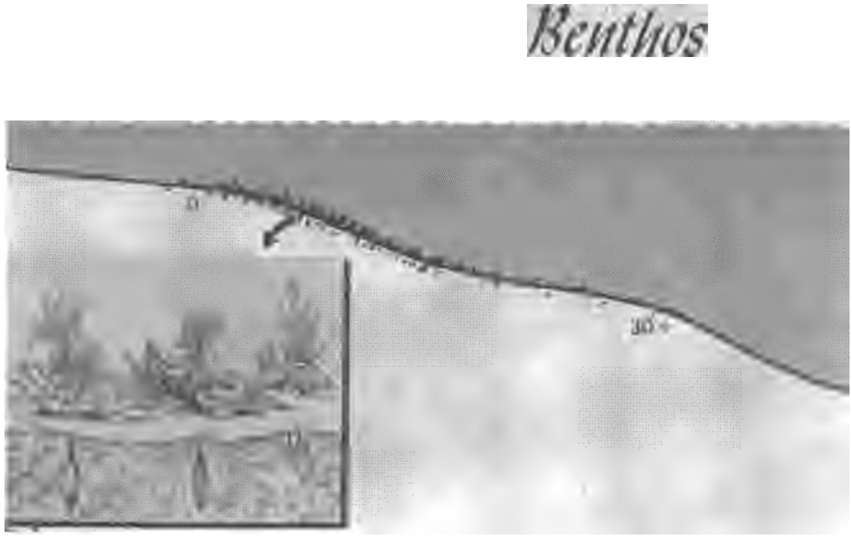


Figure 22

Along the length of the estuary, the benthic populations range from fresh to marine environments, but the densest beds are often near the center of the system. Each community is complex (Fig. 22) and greatly affected by the surrounding biological community and abiotic environmental conditions. The oyster, for instance, is notable for its ability to tolerate high sediment concentrations, temperature variations from near freezing to summer heat, and salinities from about five parts per thousand to oceanic concentrations. The real distribution of oysters, however, is frequently controlled by three factors. The upstream limit is set by the maximum flow of fresh water from the river. The downstream limit is set by predators and parasites (boring snails, starfish, fish, and microscopic organisms) which occur only in high salinities. Its lateral spread is limited by the too-soft sediments of many channels, so that the oyster (and other molluscs) are most abundant on the shoal, firm channel shoulders (Fig. 23).

The sessile benthic estuarine species possess unique advantages and offer some of the greatest opportunities for aquaculture. They occur close to shore and are accessible, they are sessile and can be owned by the culturist, and they have high commercial value. Especially significant is the fact that they feed very near the beginning of the food chain, where the quantities of available food are greatest. Some species can also be reared in hatcheries, making it possible to breed superior strains for fast growth or other desirable characteristics.

The aquatic species which can swim faster than usual water currents, and can

Figure 23

therefore control their distribution and movements, are called nekton. Most of these are fish, and most of the valuable coastal species are totally or partially dependent upon the estuaries. Some fish are herbivores, feeding on microscopic plants by filtration or on larger plants. Others are carnivores, which catch smaller animals. Some of the finest game fish are super-carnivores, pursuing and capturing other fish. Most species, in fact, change their feeding habits drastically as they grow from tiny larvae to post-larvae to juveniles to adult fish. A striped bass might depend in turn on phytoplankton, copepods, possum shrimp and, eventually, a mixture of fish and larger invertebrates. Fish use estuarine waters in several different ways, and typical species illustrate those uses.

The striped bass is one of the great estuarine species of the world, providing excellent fishing for both food and pleasure. In many bays and rivers, it spawns near the interface of fresh and low salinity water (Fig. 24). (Some move farther

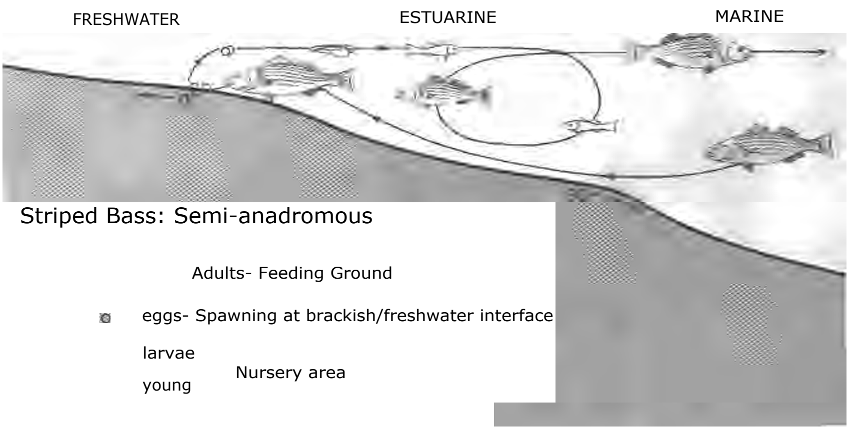
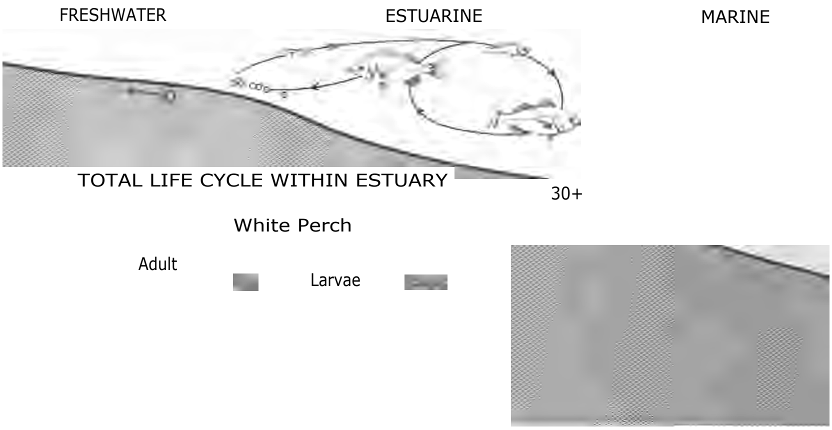


Figure 24

into rivers, and a few striped bass populations are adapted to fresh water.) In the estuary, the eggs and larvae drift downstream (past the area of heaviest silt) and the developing fish feed throughout the system until they reach maturity and repeat the cycle. There are several subpatterns, involving movement of small fish to shoals, winter congregation in deeper water, summer dispersion, and coastal migration by part of the population. Each demonstrates the remarkable compatability of the estuary and this species. There is even some suggestion that the early effects of enrichment of estuaries by human waste disposal may have been beneficial to this species. The white perch, a member of the same family of fishes, follows a similar pattern (Fig. 25), except that populations do not range as far in the large estuarine systems. Both of these are semi-anadromous fish, which move from saline water to, or almost to, fresh water for spawning.

Anadronious species are well exemplified by the herrings, the salmons, and the shads. The American shad spawns only in fresh water, the young browse in the estuary during their first summer and the next 3 to 4 years are spent in the open ocean (Fig. 26). Utilizing sensory systems which are almost incredibly selective (and very poorly understood), most return to their river of origin for spawning. For such species, it is obvious that the environmental quality of the entire estuarine system must be within the tolerance of the species, or the life cycle will be broken. The homing instinct is almost certainly guided by extremely small quantities of chemical substances in the water. Therefore, it is conceivable that one or more of the many exotic chemicals now seeping and



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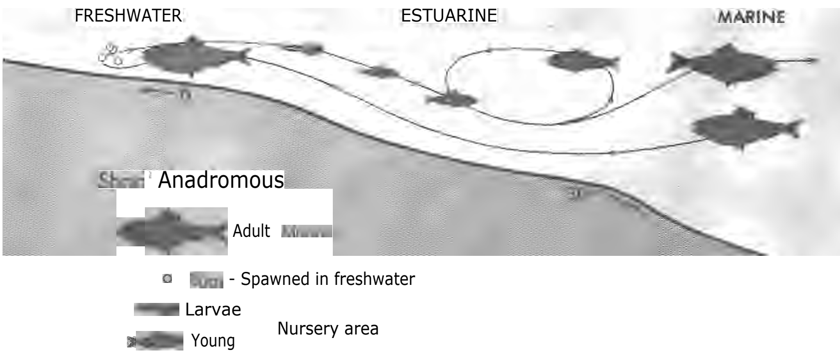

Figure 26

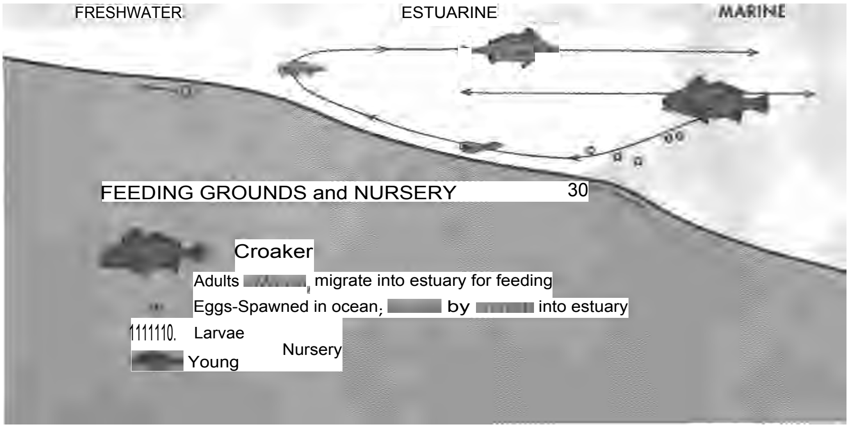

Figure 27

dripping into estuaries may interfere with the delicate sensory systems or mislead or confuse the fish on their urgent migration to the spawning grounds. Such a subtle sequence could destroy a population with very little chance that the cause could or would be detected.

Another group of fish regularly utilizes the complex circulation system of the estuary by spawning at the entrance to estuaries. The croaker is an example on the Atlantic coast. The young are rather rapidly transported upstream in the saltier deep water to reach the plankton-rich low salinity area (Fig. 27). Several members of the drum family, the menhaden, and other species use the inherent movement of water in this way.

Many of the species which live in the open ocean or over the continental shelf, such as bluefish, move into the estuaries to feed on the abundant biological crops that occur there (Fig. 28). In fact, most oceanic species occasionally enter estuaries, and some undertake regular seasonal feeding forays into them.

All of these patterns of use exist simultaneously as each species follows its own seasonal sequence. The resulting complexity of movement (Fig. 29) may include the regular or occasional presence of up to several hundred species. Many of these species are dependent both on the estuary, itself, and upon availability of clean water and a favorable environment in all of the areas they utilize.

The low salinity portion of many estuaries is a region of exceptional value to fish. This region receives fish eggs, larvae, and young from freshwater spawners,

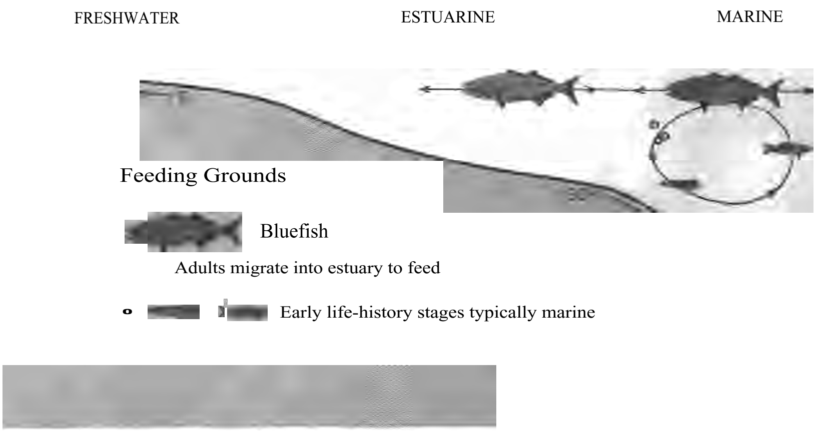

Figure 28

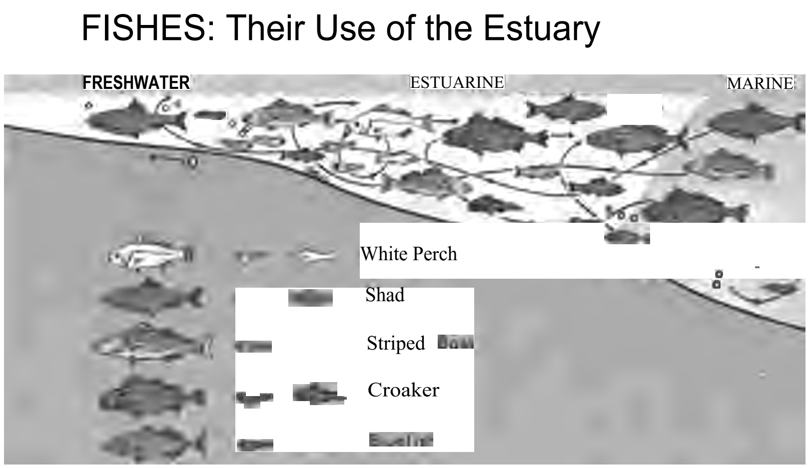

Figure 29

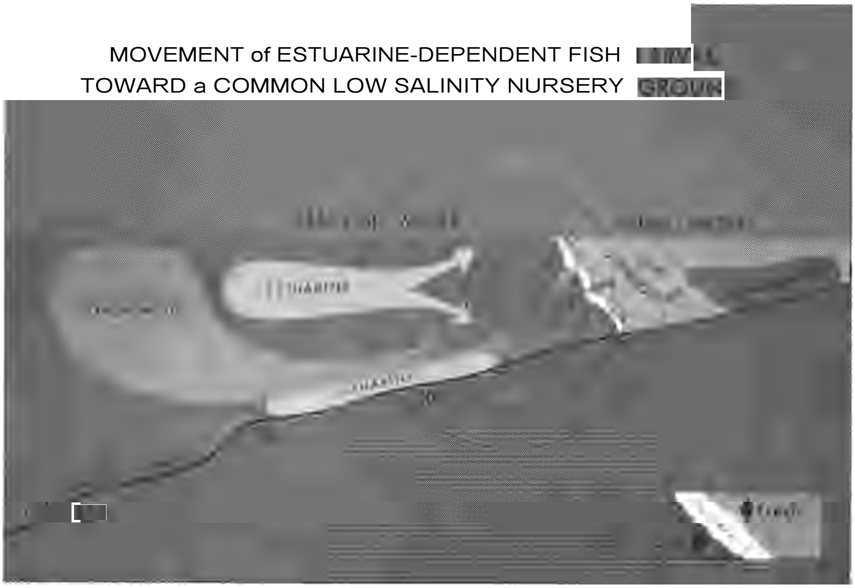

Figure 30

semi-anadromous and anadromous fish, estuarine spawners, and some of those that spawn in the lower estuary or ocean (Fig. 30). This region therefore becomes a resource of unique importance. Its high value is not obvious, however, since these stages in the life history are not visible to anyone except those who employ the highly specialized collecting gear (Fig. 31) that is required to reveal the diversity and abundance of young fish and their food. These rich fish nurseries that are the estuaries merit special care and protection; it is a threatening coincidence that many cities are located near these regions close to the head of navigable deep water.

The species which have successfully adapted to estuarine circumstances are not numerous in comparison with tropical or oceanic species. When they are well adapted, however, they are often exceptionally abundant. Within the groups briefly discussed, copepods, jellyfishes, oysters, clams, worms, striped bass, white perch, anchovies, herring, and many others provide examples of remarkably high population densities.

Among those species which are exceptionally well fitted for the estuarine environment is the blue crab, which spawns near the ocean to produce planktonic zoea larvae (Fig. 32). The megalops, or second stage larva, settles to the bottom and subsequent post-larval stages are widely dispersed by the *upstream* deepwater drift. The juvenile crabs semi-hibernate during cold weather

Figure 31

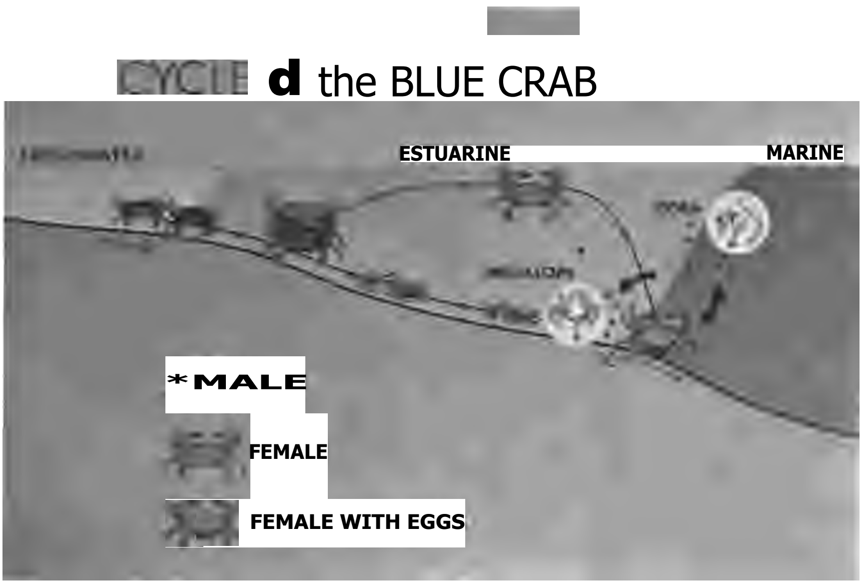

Figure 32

Figure 33

(north of the Carolinas, not south) and continue to shed their exoskeletons and grow. Mating occurs in middle and low salinities and the females move rapidly back to the spawning grounds, perhaps gaining some advantage from the net *downstream* drift of surface water. Here is a composite example of use of the circulation patterns, dispersion to rich feeding areas, dependence on the integrity of the entire system, and high (though widely variable) abundance. Perhaps the blue crab is an appropriate biological symbol of the estuary.

IN CLOSING

These features of the physics, chemistry, geology, and biology of many American estuaries existed when this continent was first discovered by people from other land masses. Subsequent migration, population expansion, and dramatic technological development have rather suddenly placed enormous additional stress on many useful but fragile estuaries (Fig. 33). Perhaps this brief summary of the rich biological systems involved can assist rational and effective efforts to live in enduring harmony with the complex and sensitive ecosystems of these valuable but vulnerable bodies of water.

ACKNOWLEDGMENTS

We wish to express our special appreciation to Dr. Donald W. Pritchard and his associates at the Chesapeake Bay Institute of The John Hopkins University for their excellent contributions to knowledge of the physical and chemical nature of estuaries. The summary and illustrations presented here for salinity distribution, stratification, patterns of water movement, and other environmental features are based in large part on their research and publications.

The staff of the Chesapeake Biological Laboratory has provided more assistance and encouragement than we can possibly cite. Most of the photographs are by the senior author, but some were taken by others and "loaned," to disappear in his collection. Mr. Michael J. Reber has been exceptionally imaginative in assistance with the diagrams. Other colleagues have been kind enough to review the manuscript and offer constructive suggestions for reducing a complex body of incomplete scientific knowledge to a communicable general description.

If thanks can be given to an atmosphere, we express our appreciation to the informal and stimulating spirit of the Atlantic Estuarine Research Society, where so many ideas about estuaries have been presented and discussed until they were either matured or abandoned.