


Reports

2003

The Chesapeake Bay : a synopsis

William J. Hargis Jr.
Virginia Institute of Marine Science

Follow this and additional works at: <https://scholarworks.wm.edu/reports>

 Part of the [Atmospheric Sciences Commons](#), [Climate Commons](#), [Geology Commons](#), [Hydrology Commons](#), [Marine Biology Commons](#), [Oceanography Commons](#), [Other Environmental Sciences Commons](#), [Sedimentology Commons](#), [Sustainability Commons](#), and the [Terrestrial and Aquatic Ecology Commons](#)

Recommended Citation

Hargis, W. J. (2003) The Chesapeake Bay : a synopsis. Virginia Institute of Marine Science, College of William and Mary. <http://doi.org/10.21220/V5HS33>

This Report is brought to you for free and open access by W&M ScholarWorks. It has been accepted for inclusion in Reports by an authorized administrator of W&M ScholarWorks. For more information, please contact scholarworks@wm.edu.

The Chesapeake Bay: A Synopsis



WILLIAM J. HARGIS, JR.

Emeritus Professor of Marine Science
Virginia Institute of Marine Science
School of Marine Science
College of William and Mary

710-1100
1110
87
104.5
045
11874
0003

Dedications

This small book is dedicated to the memories of my recently-deceased colleagues and friends, Dr. L. Eugene Cronin and Dr. Donald W. Pritchard of Maryland. Both were highly accomplished and acclaimed estuarine scientists who contributed significantly to knowledge and appreciation of the Chesapeake Bay and similar natural systems everywhere. Dr. Cronin was a major contributor to our knowledge of the blue crab but is best known for explaining the importance of the Chesapeake to society and its posterity. Dr. Pritchard was the foremost contributor to our understanding of the physical phenomena of the Bay. Both taught us much and our institutions, the Chesapeake Bay Institute of Johns Hopkins University (Pritchard), the Chesapeake Biological Laboratory of the University of Maryland (Cronin) and the Virginia Institute of Marine Science of the College of William and Mary (Hargis) provided most of the professional core and much of the cash for the Chesapeake Research Consortium, Inc., which also included the Smithsonian Institution when we formed it in 1971! They are greatly missed!

Acknowledgments

Kay B. Stubblefield assisted in the preparation of the illustrations and numerous drafts of the original manuscript and subsequent editions. Shirley O. Sterling prepared drafts for the additions for the third edition, which incorporated major revisions. Ruth A. Hershner prepared drafts for this, the fourth edition. Evon P. Ruzecki assisted with hydrographic and meteorological concepts as did Carl H. Hobbs III, Gerald H. Johnson, and E-an Zen with geological ones. William G. MacIntyre provided useful information about the chemistry of Bay waters. Responsibility for errors of currently-accepted concepts ("facts") or of conclusion rests with the author. (Should any be noted, please notify him at VIMS/W&M, Gloucester Pt., VA. 23062, or by e-mail at wjhargisjr@aol.com). Wanda W. Cohen encouraged the project, contributed most of the glossary and supervised the early publishing.

This booklet was originally presented as a public lecture in Richmond at the Science Museum of Virginia on Sunday, January 11, 1998. It has been revised several times since, with additions and corrections as available and necessary.

The antique map by Herman Moll presented on the cover was published in *Oldmixon's British Empire in America in 1708*. The "quaint" spellings are as he presented them.

Revised April 2003

© 2003 by the VIMS Press

Preface

The mighty Chesapeake is the largest **estuary**¹ in the United States. Like the mountains in which its major tributaries—the Susquehanna, Potomac and James Rivers—arise it seems eternal. It is not! It is young. It reached its current dimensions about 2,500-3,000 years ago. And, like the mountains, it is changing; but much more markedly and rapidly than they.

Extremely productive biologically, the Chesapeake has produced and yielded millions of bushels of Eastern Oysters (*Crassostrea virginica*) and Blue Crabs (*Callinectes sapidus*), Hard Clams (*Mercenaria mercenaria*) and tons of commercial (Atlantic Menhaden—*Brevoortia tyrannus*) and edible (many species) finfishes² over the seven or so millennia of the development, use, and (very recently) exploitation of “our” Chesapeake. This, too, is changing.

Humans of Asian beginnings (American Indians) observed the evolution of the mighty Chesapeake as **Holocene** (Epoch) global warming progressed and sea level rose to fill its basin. Over the last four centuries, people of western (European and African) origins have played increasing roles in its exploitation and apparent decline. More recently, latter-day immigrants from Asia and elsewhere in the near and far east have joined them. Together, their progeny will affect its future.

In 2007 AD, Virginia will celebrate its 400th year. Maryland’s 400 year Centenary celebration will follow in due course (2034 AD). The Chesapeake Bay, on whose shores the first permanent European settlement in the United States³ north of Florida occurred, played a prominent role in the development of both states, the United States and North America. It is fitting at this point to feature the natural history of the Bay and briefly describe and discuss its geophysical features and biota, their past and importance and their likely future. While doing so we may be able to cast some light on some of the natural resource and environmental problems of interest today—oyster and finfish diseases and declines, faltering Blue Crab catches, declining water quality of the Bay and its tributaries, diminishing wetlands, and even “Global Warming.”

¹ Words in bold are defined in a glossary at the end of this booklet.

² See the excellent book on *Fishes of the Chesapeake Bay* by Murdy, Birdsong and Musick (listed in the bibliography section, for a listing of finfishes not specifically mentioned above.

³ Saint Augustine, Florida was established by the Spanish in 1565. Saint Johns, Newfoundland, an early fishing community, was apparently begun as early as 1528 by persons from various European nations. England took it over in 1583. Thus, it became the first permanent English colony on the North American continent.

Introduction

• Much has been written about the Chesapeake Bay, especially in the last half-century. It is extremely popular with regional readers and writers, notably in Maryland where mere inclusion of the words “Chesapeake Bay” in a title seems to guarantee demand. A large number of “coffee table” picture-essay books, nonfiction works and even novels have been

published. New ones “hatch” each year—seemingly. (See the Suggested Reading List below). This is not surprising considering the Bay Basin’s size and its role in the history and development of our country and five of the thirteen founding colonies—Virginia, Maryland, Delaware, Pennsylvania, and New York.

Table 1. *Recognized periods of Indian occupation of the Chesapeake Bay Region.¹ (Some 14,000 - 12,000 years, possibly more.² Oldest to most recent.)*

(See Glossary) PRE CONTACT	Period	Length (Years) (modified from Barker and Roberts, 1979)	Probable time Period (modified from McCary, 1957)
	Paleo-Indian	4,000	12,000 BC - 8,000 BC
	Early Archaic	2,000	8,000 BC - 6,000 BC
	Middle Archaic	3,000	6,000 BC - 3,000 BC
	Late Archaic	2,000	3,000 BC - 1,000 BC
	Early Woodland	1,000	1,000 BC - 0 AD
	Middle Woodland	1,000	0 AD - 1000 AD
	Late Woodland	600	1000 AD - 1600 AD
	Historic	400	1600 AD - Present ³

¹ Adapted from Barker and Roberts (1979) and McCary (1957), with assistance of Professor Dennis B. Blanton of the College of William and Mary.

² Recent archeological findings have extended (pushed back) the earliest dates of the Paleo-Indian Period to around 14,000 BP, or approximately 12,000 BC. Some archaeologists are confident only of 12,000 BP (or 10,000 BC), preferring to await firm confirmation of older dates, some of which reach back to around 15,000 BP.

³ McCary (1957) estimated an approximate population of 9,000 individuals in the Powhatan Confederacy in 1607 when the Jamestown settlers arrived. According to McCary, the total number of Indians in Virginia at that time was some 18,000 individuals of over 40 tribes (30 in the Powhatan Confederacy alone) of three linguistic stocks [Algonquian (30+ tribes—eastern Virginia), Eastern Iroquois (Nottoway, Meherrin and Cherokee—southern Virginia and southwestern Virginia) and Siouan (Manahoac, Monacan and Saponi—northwestern and western Virginia)]. It seems that three other Siouan-speaking groups, the Tutelo, Mohetan and Occaneechi lived in west central and south central Virginia, respectively. Doubling the total estimate of Virginia Indians to secure an estimate of the numbers living in the Chesapeake Bay region (Virginia, Delaware, and Maryland) in 1607, yields some 36,000 individuals.

- The Chesapeake seems to have been adopted as a—perhaps *the*—national estuary during the last thirty-five years as scientific, political and public attention has been focused on the environment—especially the fragile and dynamic coastal zone where people tend to congregate in our country and the world over. The growth of *effective* scientific and public interest and advocacy in the Chesapeake is partially responsible. Real and/or apparent declines in the quality of the environment and the availability of wildlife and fishery resources have contributed as well.
- Despite overly-effective propagandizing by New England partisans, the Chesapeake Bay, not Cape Cod Bay, was the first ultimately successful entry point for European settlers on the eastern seaboard of North America north of Florida and south of Newfoundland. The human population in the states bordering the Chesapeake System, relatively low in *Indian* and early colonial times, has grown ever since (see Tables 1 and 2).

Table 2. Population Levels in the Chesapeake Bay Region—all figures approximate.

Founding Date (AD)	Date of Census Est. (AD)	VA	MD	Total
1607 (VA)		105		
	1625 ¹	1,095 ²		
	1630 ¹	2,500		
1634 (MD)	1635 ¹	5,000	200-300	ca. 5300
	1660 ¹	27,000	8,000	35,000
	1700 ¹	58,000	30,000	88,000
	1960 ³	2,203,000	3,167,000	5,370,000
	1980 ³	3,174,000	3,726,000	6,900,000
	2000 ³	4,133,000	4,071,000	8,204,000

¹ Adapted from Barker and Roberts (1979).

² Between 1607 and 1625, 7,500+ additional immigrants had arrived at the Virginia Colony. By 1625, famine, unsanitary conditions and foul drinking water, disease and Indian massacre (350-400 settlers killed in 1622) had reduced the colonial population of Virginia to some 1,095. Considering this level of attrition (ca. 86%), it is a wonder the early Virginia Colony persisted.

³ From Culliton et al. (1990).

The Chesapeake Bay Ecosystem

The Bay¹, itself, is an estuary, a semiconfined body of water connected directly (or indirectly) to the ocean within which freshwater from the land meets and mixes with salty water from the ocean. Because of their oceanic connections, estuaries contain waters which range from fresh in their upper reaches, to brackish in their middle reaches and finally, to salty near their mouths. All estuaries are subject to the astronomical tides generated in the oceans into which they open. The nature of estuaries depends upon a number of geographical, geological, chemical, physical and biological factors, **all** of which can be severely altered by man.

Geomorphology of the Chesapeake (Figure 1)

Statistics (approximate)

- Length-195 statute miles (sm)
- Width - 16 sm, mouth, 30+ sm, off Potomac River mouth, 4 sm, head of the Bay
- Depth (Av.) 21 ft. (6.4 meters-m)
- Depth (Max.) 174 ft. (53.0 m)
- Principal Rivers²

Susquehanna	York
Potomac	Choptank
James	Chester
Rappahannock	Patuxent

The actual freshwater discharges of the Bay's tributaries vary depending on precipitation in their watersheds. However, the average annual estimated freshwater contributions (i.e. inflows to the Bay in percentages of the total) are as follows: the Susquehanna River (~49%),² the Potomac River (~18%), and the James River (~16%); therefore, these three Western Shore Rivers provide some 83% of **all** riverine (or surface) freshwater entering the Bay, as measured at applicable gauging stations (see Figure 2).³

All of the other drainage basins, including those of the Rappahannock, York and Patuxent Rivers on the Western Shore, contribute almost all of the rest (i.e. less than 20%). Obviously, the Upper Bay tributaries of the "Western Shore" north of the Patuxent and all of the Eastern Shore rivers and creeks, including the Chester, Choptank, Nanticoke, Wicomico, and Pocomoke Rivers from north to south), add the smallest quantities of freshwater. These freshwater inflows

and other factors, such as the **Coriolis Effect**,⁴ assure that salinities are higher on the Bayside of the Eastern Shore than those of the waters at comparable latitudes on the Western Shore (see Figures 1, 2, 9 and 10).

The largest volume of water in the Chesapeake Bay comes from the nearby Atlantic Ocean as is shown by the fact that total outflow of water between Capes Henry and Charles is some nine (9) times the volume of freshwater known and estimated to be contributed by all of the tributaries. Because of the difficulty of measuring the subsurface drainage from the various **aquifers** around the Bay, the average amounts of freshwater they contribute annually remains to be accurately established. Since nutrients and pollutants can be carried into the Chesapeake by subsurface as well as by surface discharges, by wind (aeolian), and by direct precipitation into its waters, accurate estimates of their respective contributions are important to effective management of the Bay's water quality.

- Drainage Area - 64,000 mi²
- Surface Area - 7,000 m²
 - Bay proper - 2,500 mi²
 - Bay tribs. - 4,400 mi²

- Shoreline
 - Bay proper - 4,000 + mi
 - Bay tribs. - 8,100 + mi.

[Over 25 years ago the *tidal shoreline* of Virginia was carefully **planimetered** by VIMS' scientist Roger Buck. Over 7,000 sm were recorded. Doubling to include MD and Delaware (probably a conservative approach) would yield a total linear shoreline of some 14,000+ sm.⁵ Since shoreline is highly valued and usually assessed and/or sold by linear measurements, accuracy in estimates of shoreline length is important but extremely difficult to obtain.]

¹ The Chesapeake is connected directly to the Western North Atlantic, called the *Virginian Sea* by Captain John Smith and other explorers and mapmakers in the offing of Virginia, Maryland and Delaware.

² The notation (~) means approximately.

³ In order depending on the size of their drainage basins

⁴ Due to the rotation of Earth (see glossary)

⁵ This estimate does not include the shorelines of the upper Susquehanna drainage basin in Pennsylvania and South-Central New York (Figure 2).

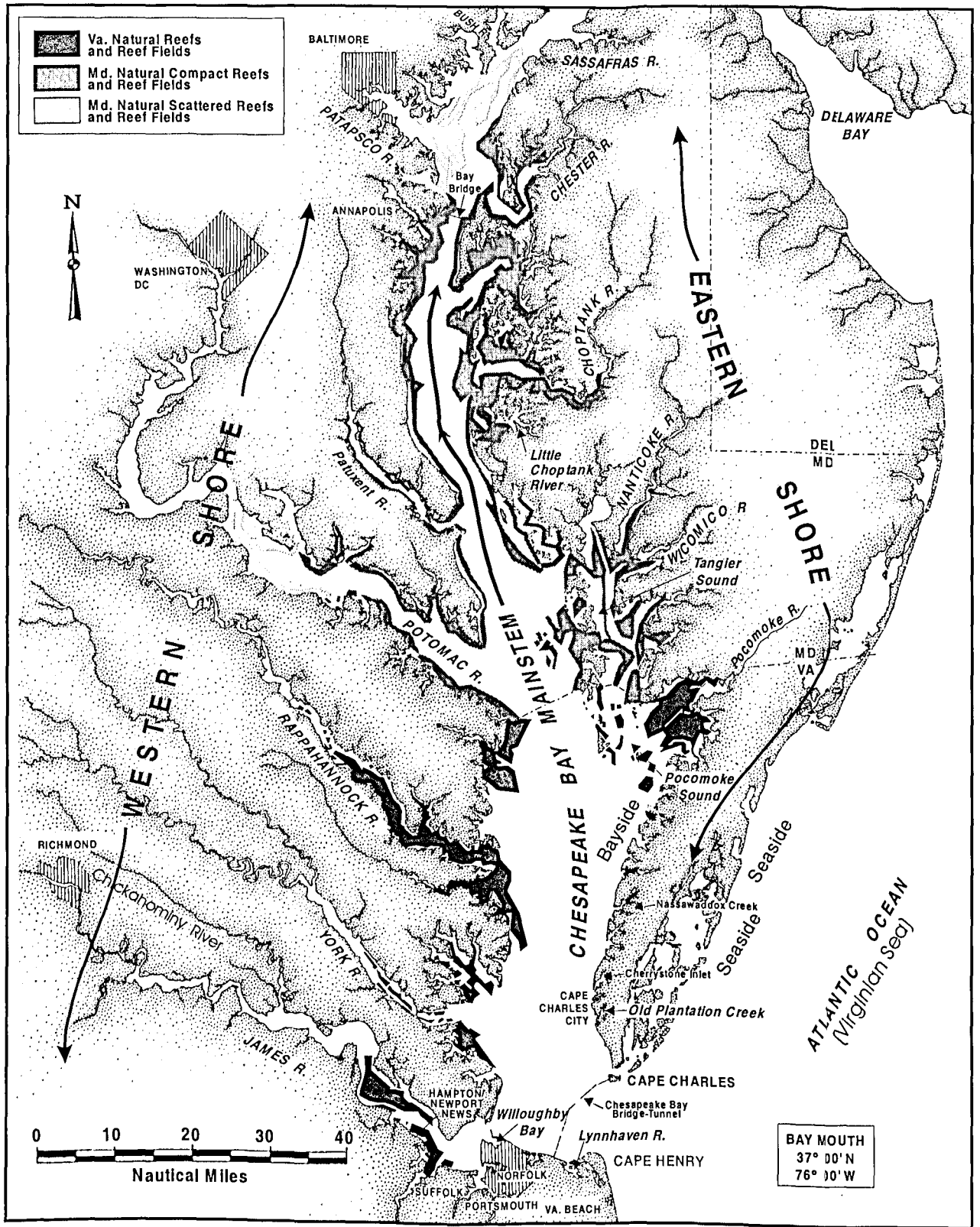


Figure 1. The Chesapeake Bay and its tributary subestuaries, showing principal tributaries and distribution of the oyster reef system extant in the late 1800s (Hargis 1999).

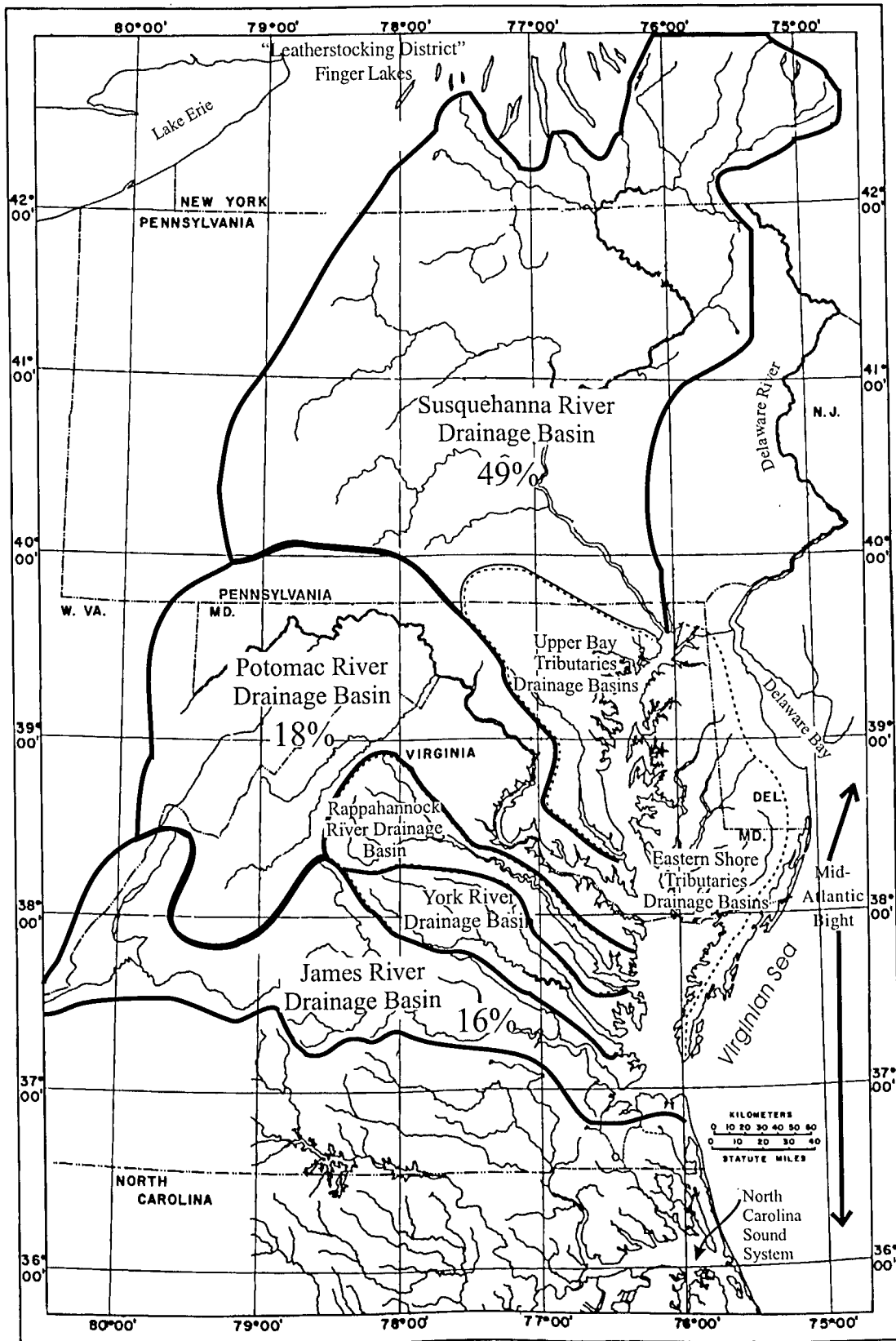


Figure 2. The Chesapeake Bay drainage system showing the average annual freshwater inflows of the three major drainage basins. The Susquehanna, Potomac and James, comprising most (about 83%) of the overall drainage area and contributing most of the Bay's annual riverine freshwater inflow, are clearly defined.

- Wetlands - 498,000 acres
- Water volume - 18 trillion gallons of oceanic and fresh water (1 year to fill if drained and stopped off).
- Average flow volume 70,000 f³ sec. (2,000 m³ sec).
- Total flow out (outflow) - 68 billion m³, exceeds currently known (and estimated) freshwater inflow by about 9:1.
- Ocean tides, diurnal - 2 highs and 2 lows daily.

Salt water injected into the bay by the inflowing ocean-derived current [normally at about 32‰ (parts per thousand) by weight] makes Bay water brackish as it mixes with the fresher water introduced by riverine run-off with salinity decreasing with distance from the Bay mouth. Tides, gravity, density differences, chemical mixing, earth's rotation (Coriolis effect) and, less regularly, winds provide the energy which sustains a complex water movement system—usually two-layered with the lighter, fresher above and the heavier, saltier water beneath in the Bay and its major tributaries.

Basin Shape

Dimensions of the current Chesapeake basin presented above are approximate, as they must be. The Bay is dynamic and its geographic features constantly change. The lengths, contours and elevations of shorelines and wetlands are altered by erosion and deposition as are those of the shallows and deeps by scouring and deposition. Man's activities affect them all. Measurements of physical features made today will be different tomorrow. All geomorphological statistics are approximations of the way things were at, or over, some period of time. Thus, it has always been. Thus, it will be. This variability causes great difficulties for estuarine scientists as they attempt to study the Bay and determine the normal and abnormal processes and causes of change. Even as scientists work their subject is changing. The Bay is a chimaera!

As stated, the Chesapeake Bay is relatively young. Its basin began to fill as the **Wisconsinan**

ice cap melted and the resultant rising "Atlantic" ocean waters reached the approximate longitude of the present capes (Cape Henry and Cape Charles) some 7,500 years ago (7,500 BP). After some 4,000 years of filling of the basin of the developing Bay system at rates which varied with ice cap melting as "persistent" atmospheric temperatures varied (as they still do) the present geographical dimensions of the Bay were attained—approximately. Fishermen, sailors and other navigators of today would have been able to recognize the shorelines and most prominent landmarks of the Bay and its tributaries as they appeared some 2,500 years ago when filling "slowed". Since then those dimensions have continued to change. The Bay as a system is highly dynamic, varying hourly, daily, weekly, monthly, seasonally and yearly as the tides ebb and flood, rain falls in the watershed, ice forms and snow falls and both melt, sedimentation increases or is reduced due to changing rates of upland and shoreline erosion, and storms and other natural forces act upon it. These same factors have affected the Chesapeake since its beginning, but recently man's activities have also impinged upon it—increasingly, as numbers, ambitions, and the land-altering technological capabilities of humans have grown in its watershed. In early Colonial times agricultural and associated deforestation were not significant. More recently, however, development of larger agricultural, industrial and housing sites, towns and cities and transportation corridors with associated deforestation have wrought major geographic changes.

Geological Evolution of the Bay

Returning to the geological beginnings of "our Bay." The valleys of the future Susquehanna and James Rivers and their tributary watercourses constituted the pre-Wisconsinan Ice Age basin of the future Chesapeake—roughly speaking. These were dominated by the land masses, on or in which the river systems originated and through which, they flowed. During the Wisconsinan (the last) Ice Age the Laurentian glacier extended as far south as the present-day city of Sunbury, PA,

some 40 miles (64.4 km) southwest of Wilkes-Barre, at the confluence of the Northern and Western Branches of the Susquehanna River system. As it flowed slowly southward the glacier molded land contours in and around both branches of the future upper Susquehanna basin (Figure 3). The melt waters beneath and at the southernmost “leading” (later receding) edge of the ice cap undoubtedly influenced subsequent development of the future Susquehanna River Valley as well by their erosive forces.

As with all terrestrial and aquatic landscape features, tectonic and erosive forces and even some catastrophic events affected the Chesapeake basin in ages past. For example, there is convincing evidence that a substantial bolide (a comet, meteor or meteorite) struck the lower “Bay” area west of present-day Cape Charles City some 35 million years ago. Subbottom soundings and borings indicate that the resultant crater was at least 85 km (52.8 miles) in diameter and 1.3 km (0.81 mile) deep—some three times larger than any other bolide crater in the United States. This catastrophic event has influenced the geological and hydrographic features of the lower Bay basin ever since. However, the current Chesapeake, itself, *is not* a result of such a sudden event, but of geological and ecological processes operating over a very much longer period than the instant the bolide’s impact blasted its massive crater.

As indicated above, the basin of the future Chesapeake was dominated hydraulically by two large and probably separate river systems with extensive headwaters in the mountains, one (the Wisconsinan “Susquehanna” system, with its largest daughter—“Potomac”) much larger than the other, the future James River system.¹ Oceanic waters flooded into both of their ancient valleys which were then far offshore of the present Atlantic coastline as sea level rose to sufficient heights. Estuaries resulting from this process are often

referred to, or classified as, *drowned river valleys*.

Circulation of Water Masses in the Chesapeake System

Were there no rivers and creeks running into the Bay’s basin it would be filled with salty coastal ocean water from the nearby Atlantic, which contains about 32 parts per thousand of several mineral salts per thousand parts of the water—usually presented as ‰.²

However, as do all estuaries, the Chesapeake Bay receives freshwater from upland surface and subsurface runoff all along its lengthy shoreline, mostly from its tributary water courses. Figure 2 shows the relative contribution of freshwater runoff (inflow) of the various tributary basins. The ancient Susquehanna River and the Potomac contribute about 67%; the once-separate James basin about 16%. All three arise in the Appalachian intermountain region and their drainage basins are large. The waters of these, and lesser Bay tributaries, flow down to and over the geological escarpment (ridge—the fall line) separating the Piedmont (foot of the mountains) land mass from the much flatter Coastal Plain.³ Their gravity-driven flow gathers momentum for some distance down their lengths and continues even after spilling over the last falls at the fall line—the geographical location where the river bottom is at sea level and to which the tide reaches.⁴ The flow of the major tributaries persists into the main portion of the

² *The average salinity of water from the non-coastal reaches of the most oceans of Earth is about 35 ‰. Oceanographers generally employ this datum as the standard for ocean waters of full salinity. Water containing less than 0.5 ‰ salts is considered fresh. (Most waters of earth contain some mineral salts dissolved from adjacent land masses. But the bulk of the salts in the ocean are derived from processes taking place at the spreading zones along the massive rifts in the ocean’s floors where the tectonic plates are “born” by volcanic processes.)*

³ *The major cities of the Chesapeake Bay, Baltimore, Washington, and Richmond occur at the fall lines of the rivers on which they are situated.*

⁴ *The amount of fresh water entering each tributary of the Bay exerts considerable influence on biological, chemical, geological, and physical features of that tributary, including its biological productivity and susceptibility to pollution and its effects.*

¹ *Some geologists conclude that the Wisconsinan (or last Ice Age) Susquehanna River System and the James River System were part of a common drainage system during this time., Schubel (1981) and others think that they were separated and ran across all or part of the current continental shelf separately before spilling into the Wisconsinan Atlantic. I have employed this last concept. My principal geological advisors have not demurred.*

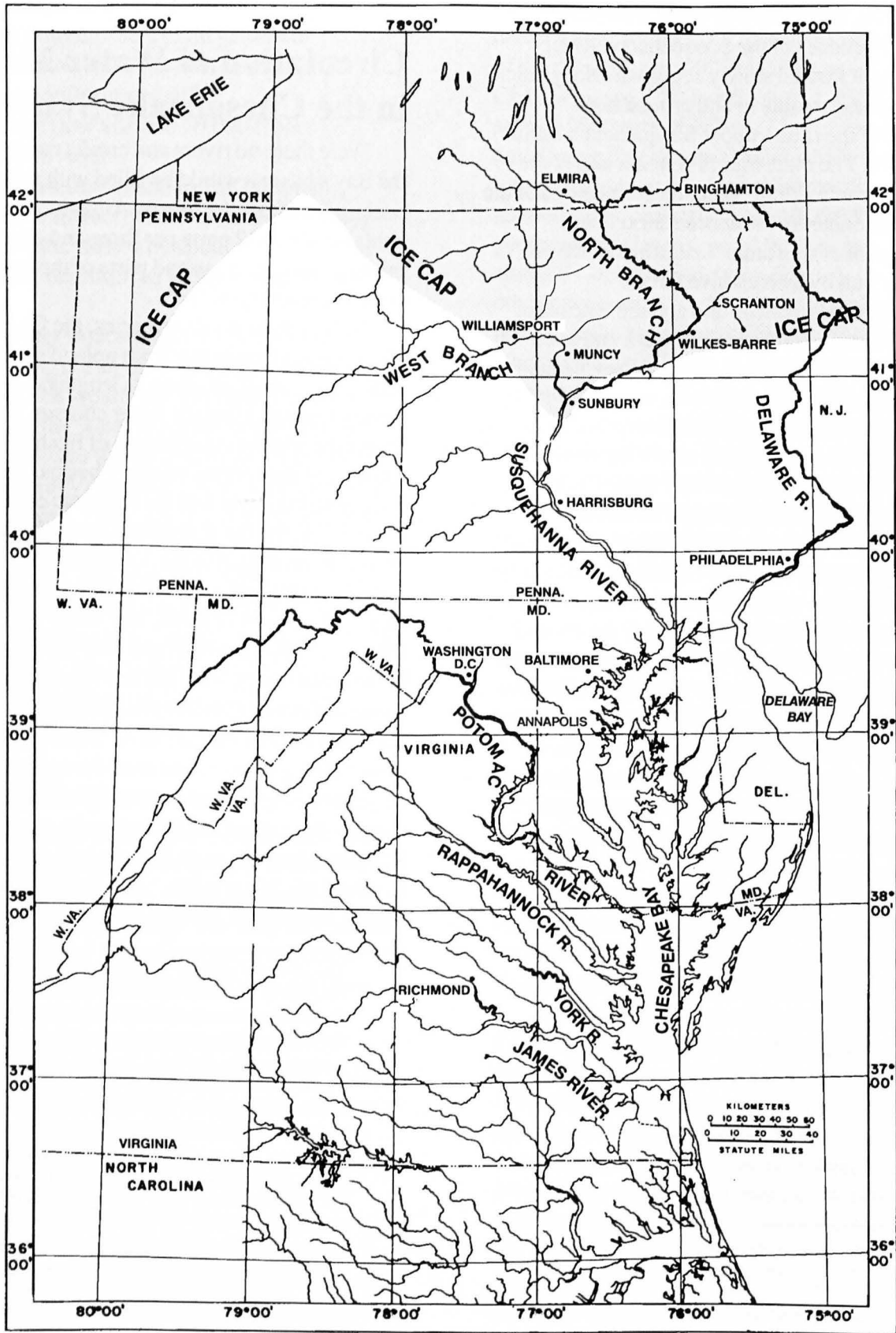


Figure 3. Distribution of the Wisconsin (the most recent) Ice Cap in the Chesapeake Drainage System.

Bay, itself. Thus, gravity is the principal driving force behind the flow of these moving waters of riverine origin as they enter the mainstem of the Bay. Due to Coriolis effect these oceanward-moving (fresher) water masses tend to remain close to the Western Shore of the Bay (Figures 1, 9 and 10).

Because of the higher proportion of mineral salts it contains, ocean-derived water is more dense than fresh water. Being heavier, this dense higher-salinity water entering the Bay from the ocean tends to remain near the bottom, beneath the fresher, lighter water from land drainage. Were there no mixing of the water in the basin this two-layered condition would persist somewhat like oil floating on water; but there is mixing—molecular and mechanical. The dilutive movement of water molecules (diffusion) between the two water masses is relatively small and largely

insignificant to our story. By far, the most important long-term mixing forces acting on Bay waters are mechanical—gravity and tidal. (Especially forceful and/or persistent winds also cause mixing—adding to the complexity of estuarine circulation.) As explained, gravity-induced riverine flow from upland regions carries the fresh water downriver, over the fall-lines of each contributory water-course and down-Bay. As the fresher (lighter) water flows oceanward, “parcels” of the saltier (heavier) ocean water below are entrained by friction and mechanical mixing into the waters of the upper layer. The ocean-derived saltier water near the bottom thus mixes with the fresher water in the layers above and both flow down and out of the Bay. The water flowing out of the Bay and into the Atlantic must be replaced to maintain water level within the Bay. Consequently, “new” ocean water flows into the

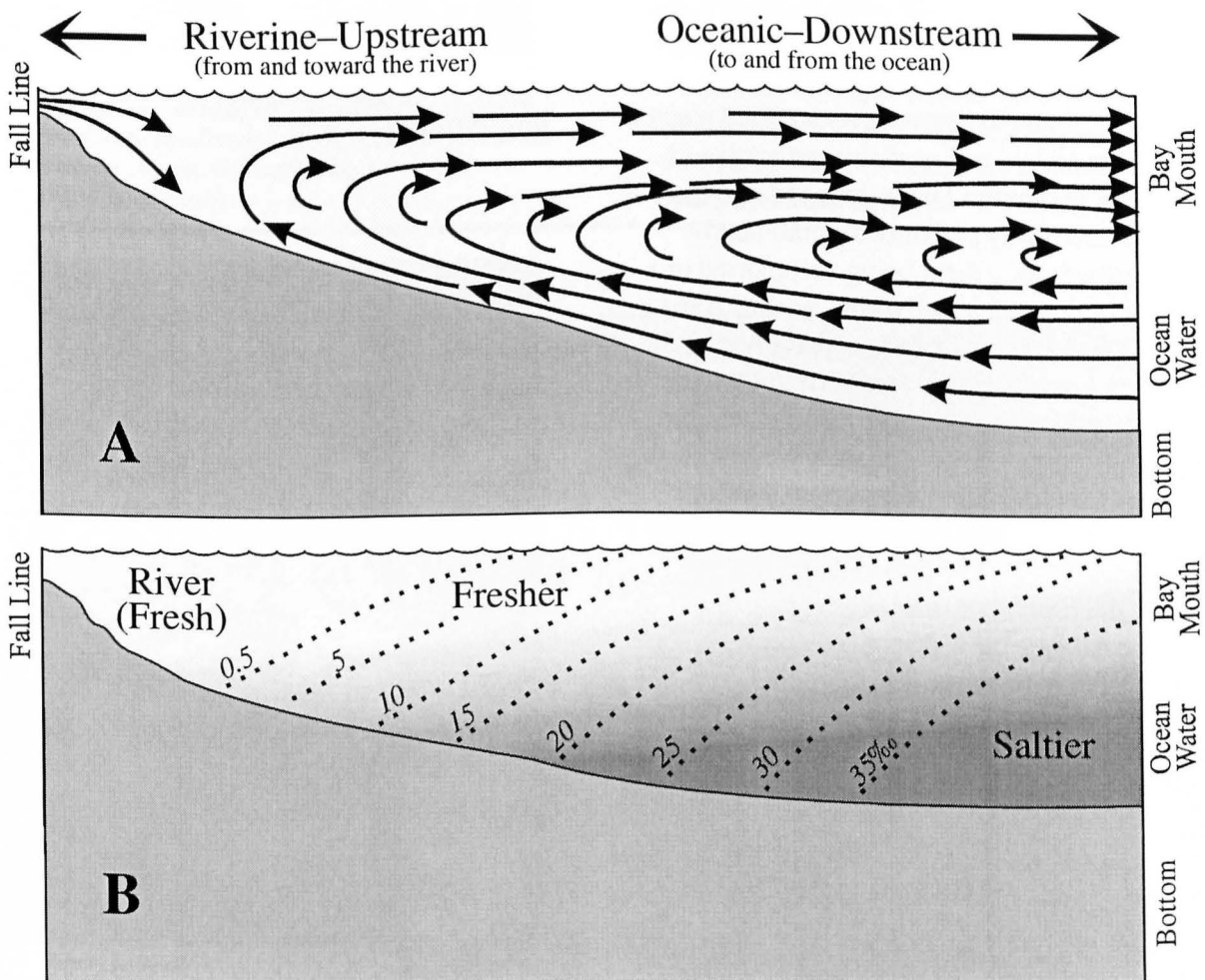


Figure 4. Showing the movement of water masses within a typical partially-mixed two-layered estuary (Figure A) and the typical vertical (through the water column) and longitudinal (up- and downriver) distribution of isohalines in such an estuary (Figure B).

basin through its mouth. This discharge-replacement action establishes a cyclic pump-like action in which oceanward-moving freshwater from the tributary rivers flows into and departs from the Bay basin in the upper layers carrying entrained ocean-derived water with it. Ocean water flows inward (mostly at the bottom) replacing its departing cohort, maintaining the water level and hydraulic balance in the Bay. This normal two-layered circulation pattern within the Bay basin is depicted diagrammatically in Figures 4A and B. In most reaches of the Bay, waters from and in both layers mixes somewhat, and the resulting diluted salinity-mixture of the water throughout most of its length is termed “brackish”.

The outward-flowing water masses in the upper layer and inward-flowing ones in the lower layer (“oceanic countercurrent”) can be observed in the nearby Atlantic as well, as Figures 5 and 6 show. These figures are based upon a VIMS study done by John J. Norcross and Dr. Edwin B. Joseph and others some 30 years ago¹ in relation to movement of fish larvae which involved dropping floating surface drifters into the estuarine and coastal waters at stations situated at varying distances north and south of the Bay mouth². Those dropped into the Bay floated down-Bay and outward into nearby coastal Atlantic waters there being transported in a southerly direction along the North Carolina Barrier islands. As these surface drifters approached Cape Hatteras they turned, drifted eastward toward the Gulf Stream and then turned northward to join the Gulf Stream (Figure 5). Appropriately weighted but still-buoyant bottom drifters dropped at the same stations sank into the deeper saltier layer of water from the ocean and flowed into and up the Bay. Many from the Bay mouth and nearby coastal waters of the Atlantic moved up-Bay sufficiently far to eventually fetch up on various shorelines around

¹ Who were interested in the transport of weakly-motile finfish larvae into and out of the Bay and its tributaries.

² The two-way water circulation pattern that these experiments detected obviously affects the geomorphological features of the Bay and its tributaries through its influences on the movements and distribution of sediments on the bottom and on deposition and scour. It could help explain the predominant sills present at the mouths of “low-flow” tributaries such as the Rappahannock and York Rivers, and their other shoaling patterns.

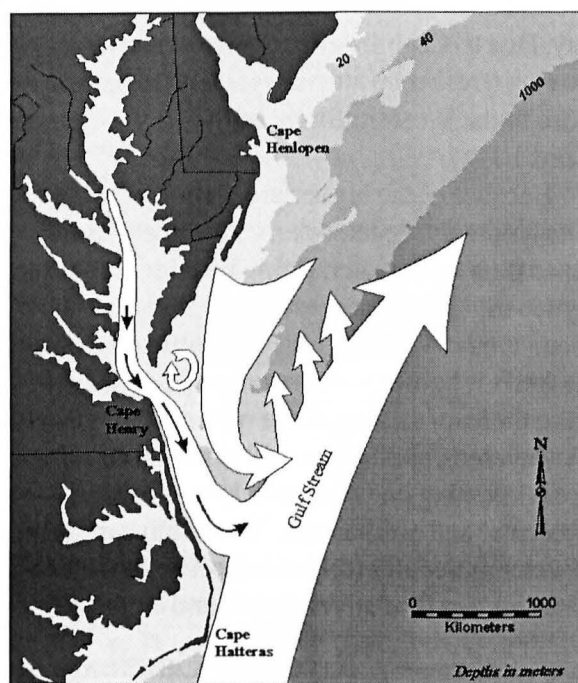


Figure 5. Surface circulation at the Chesapeake Bay entrance.

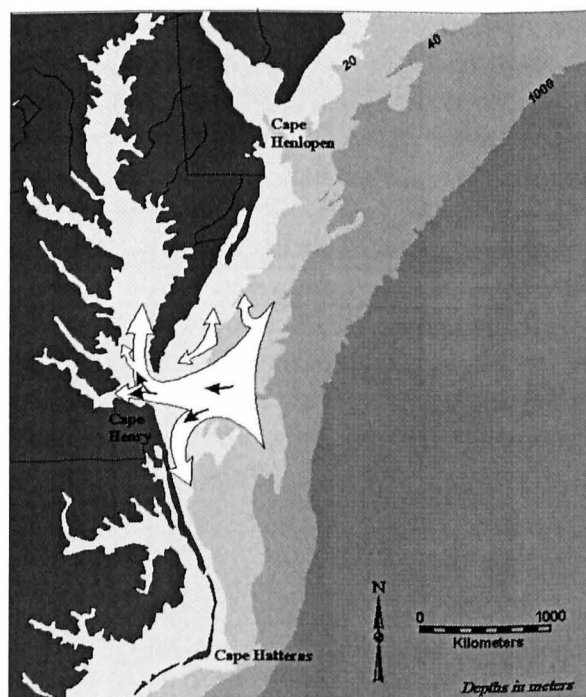


Figure 6. Subsurface circulation at the Chesapeake Bay entrance.

and below the mouth of the Rappahannock River (Figure 6)².

Obviously, floating or weakly-swimming living organisms (plankton) entrained in the outward-flowing fresher waters of the upper layer of the lower Bay would be carried outward and into the surface waters of the Atlantic Ocean, while those entrained in the inwardly-flowing heavier and deeper water masses out in the Atlantic would be carried into the Bay and could then spread throughout the Bay.¹ Conversely, those born (or feeding) in appropriately-positioned waters of the ocean could ride into the Chesapeake in this inward-moving, deeper “conveyor belt” system. The tiny larvae of many ocean-spawning fish such as Spot, Atlantic Croaker, Weakfish and Atlantic Menhaden (Figure 7) enter the Bay in this fashion each year. Blue Crab larvae, some of which are in

the nearby coastal ocean, and other weakly-swimming, “semiplanktonic” organisms do so as well (Figure 8).

This same outward/inward movement of water masses occurs in and around the mouth of each major east coast estuary. For example, estuarine waters from the Hudson River, the Delaware Bay and the Chesapeake regularly are “injected” into the coastal waters of the mid-Atlantic Bight (Captain John Smith’s Virginian Sea, Figures 1 and 2) in their seaward-flowing “plumes.” Since Atlantic coastal waters are also “sucked” into these estuaries, it is possible, indeed likely, for chemically and biologically contaminated water and fine particulates to be transferred from one estuary to another via nearby coastal ocean waters. The inward-flowing bottom waters from the ocean also carry considerable sand and other transportable sedimentary material from the ocean’s bottom into the Chesapeake and other, similar, two-layered estuaries. Living organisms from other nearby estuarine systems such as Delaware Bay and, the Carolina sound systems and the nearby Eastern Shore coastal embayments could also be transferred via this mechanism.

¹ Many weakly-swimming organisms such as oyster, blue crab and finfish larvae or floating planktonic animals and plants could be carried out of the Bay into the Atlantic Ocean (the Virginian Sea) where—under adverse conditions—some could be lost to the Chesapeake system, thus affecting year-class survival and success..

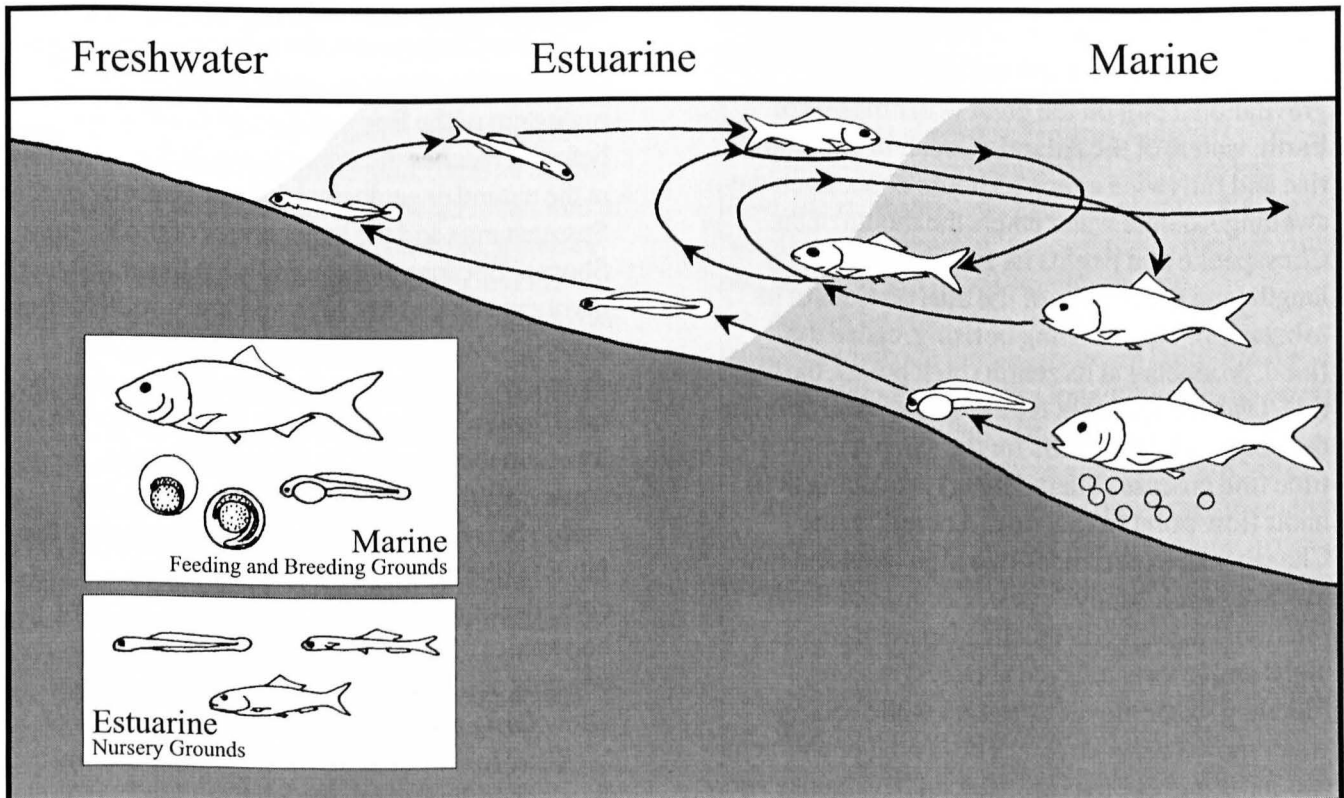


Figure 7. Atlantic Menhaden (*Brevoortia tyrannus*) Life Cycle in relation to salinity zones. Menhaden spawn in the ocean (marine) and feed and grow to maturity in the estuary.

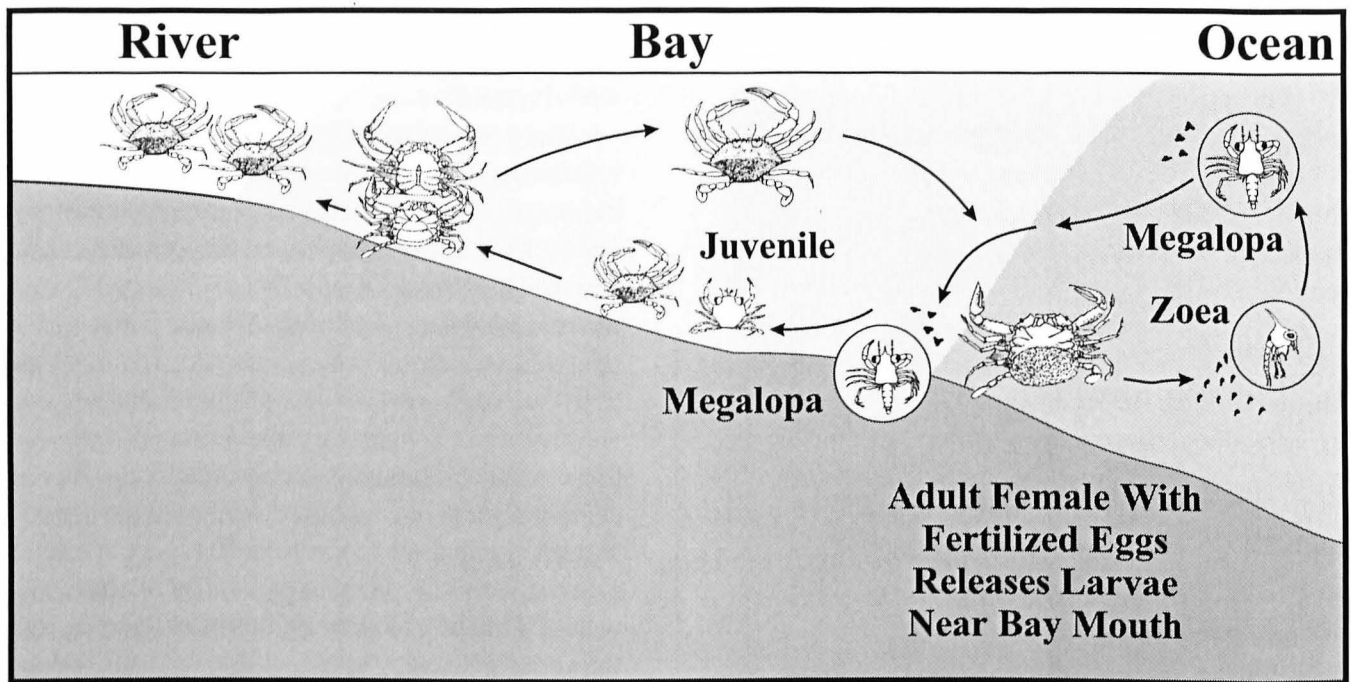


Figure 8. Blue Crab (*Callinectes sapidus*) Life Cycle in relation to salinity zones.

Tidal Mixing

The entire process of mixing between the two different water masses is predominantly affected by the “stirring” (mechanical) action produced by the tidal movement of waters. Dominated by the astronomical movements of the earth and moon relative to each other and the sun and their gravitational pull on the great water masses of Earth, waters of the Atlantic Ocean in our latitude rise and fall twice every 25 hours or so. Each day, swelling Atlantic water enters the mouth of the Chesapeake and begins its travel up the Bay’s length (and the lengths of the tidal portions of its tributaries). This swelling or rising, called the flood, producing at its zenith (high point), the high tide, lasts for about six hours. Then, water level in the ocean, and Bay, falls for the same length of time (the process called ebbing) producing at its nadir (low point) a low tide. Therefore, the Chesapeake experiences two high tides and two low tides each “daily” cycle. Because of Earth’s rotational movement, the time between successive highs and lows is delayed about 30 minutes. Flooding water moves upstream while ebbing water moves downstream. These tidal phenomena (flooding and ebbing) are “forced” by the rise and fall of oceanic water, resulting from astronomical forces. Thus, both flood and ebb progress

upstream (away from the ocean); separately—of course. When oceanic storms affect oceanic water levels near the mouth of the Bay, tidal heights are either increased or decreased, depending upon the direction, force and duration of the ocean winds and wind-driven currents.

In the Chesapeake, the tidal wave must travel considerable distances up the length of the mainstem of the Bay and then of its tributaries before it reaches the upper limits of the tidal basin at the natural or geological fall lines (mostly on the Susquehanna and the larger rivers of the Western Shore). Because of the significant linear distances involved, the times of high and low tide differ from place-to-place in the Bay depending on their distances from the mouth of the Bay. It takes the tidal “wave” somewhat more than six hours to travel up the Bay and its major tributaries, consequently, the next ebb begins at the Bay mouth before the previous flood has reached the fall line (the upper limit of the tide), thus complicating the picture. Fortunately, the tidal harmonics of the Chesapeake are relatively constant and have been studied sufficiently to allow fairly accurate predictions of the times of high and low tides at various locations around the Bay’s shoreline which are published in Tide Tables prepared annually by the National Ocean Survey of the National Oceanic and Atmospheric

Administration of the U.S. Department of Commerce. The ebb (fall) and flood (rise) of the tidal waves in the Bay greatly increase the mechanical mixing of riverine (fresher) and oceanic (saltier) waters described above.

In estuaries, the ratio between the volume of lighter, fresher water from the land and the heavier, saltier water from the ocean affects the distribution, movements and rates of mixing of those water masses as well. Distribution of sediments on the bottom are also affected. The shape and volume (geomorphology) of the estuary also influence (and are influenced by) this process as do (and are) the combined volumes of inflow of fresh surface and subsurface waters from the land masses, and the rates of those flows. Because the two water masses (riverine and oceanic) within the Bay are sufficiently different in density to maintain some “separation”¹ between them, they are semi-separated (or, conversely, semi-mixed) horizontally and, to a lesser extent, vertically and can be distinguished relatively far up the Bay and its tributaries (Figures 4A and 4B). These factors are used by estuarine scientists to classify and compare estuaries. The Chesapeake is termed a *semi-stratified* (or partially-mixed) two-layered estuary.

If one takes a series of discrete water samples vertically through the water column at strategic locations up and down and across the Bay and/or its tributaries and determines the relative amount of dissolved salts (salinity) in each sample, a picture of the distribution of the water masses and the degree of mixing between them (brackishness) can be obtained. Lines drawn between points of like salinity are called **isohalines** (analogous to isobars for atmospheric pressure on weather charts) and result in the development of charts showing the distribution of salinity in the Bay and its tributaries. This knowledge is important to biological, chemical, geological and physical estuarine scientists since salinity is a major factor affecting all estuarine processes, including sediment transport and deposition and the movement of

planktonic animals and plants, including larvae spores and seeds. In much of the mainstem of the Bay and of its major tributaries (those with significant freshwater inflow), such sampling and charting shows clearly that, on the average the saltier, heavier oceanic water is, indeed, beneath and normally can be differentiated from the fresher, lighter fresh water (mostly riverine in origin) above it (Figures 4A, 4B, 9 and 10).

The volumetric balances between the water masses (and the actual geographical distribution of **horizontal** and **vertical isohalines**) are affected by seasonal variations in the amounts of freshwater entering the systems. During years of normal precipitation (rain and snowfall) patterns in the upper watershed of the Bay, or its major tributaries, the horizontal isohalines will move downstream in the tributaries and in the Bay’s mainstem during spring, which usually experiences higher precipitation and river and **artesian** inflows. Conversely, they move upstream in the summer and fall (normally seasons with lower precipitation and lower river and artesian inflows). In response, planktonic plants and animals (phytoplankton and zooplankton, respectively), affected by such salinity changes, move up and downstream seasonally. The distribution of **isohalines** during these seasons in the Chesapeake is shown in Figures 9 and 10.

This seasonal movement of salinity up and down the mainstem and tributaries of the Bay is “duplicated somewhat” twice daily as the tide rises and falls, but to a much smaller degree.

As can be seen in Figures 9 and 10, the **isohalines** intrude further upstream latitudinally (the upstream/downstream longitudinal axis) on the eastern side of the Bay (Bayside of the Eastern Shore), than on the western side (Western Shore of the Bay) and extend further downstream on the western side.² These deflections of moving masses (to the right in the northern hemisphere) are due to the Coriolis Effect upon the moving water masses. Remember, that the fresher water from the Susquehanna, Potomac and James, and the other Bay tributaries, being gravity-driven, enters the mainstem of the Bay with some force. Remember,

¹ Obviously, since the water column is continuous from top to bottom at any point in the Bay and its tributaries the concept of “separateness” applies to the density differences between the upper and lower water masses.

² Should these geographical names and references seem confusing, refer again to Figure 1.

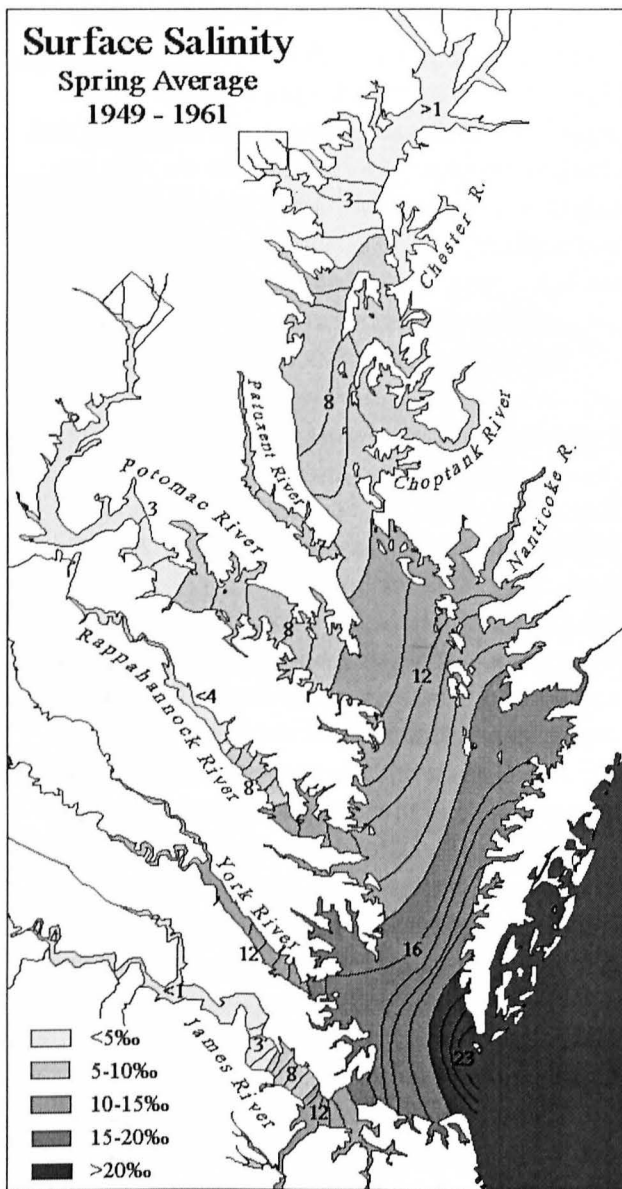


Figure 9. Distribution of average spring isohalines during the years 1949 to 1961.

also, that the major tributaries contributing most of the total freshwater in the Bay are on the Western Shore. As a consequence of their volume and gravity-driven force, the outward-flowing fresher water from those rivers tends to “hug” or flow along the Western Shore where the Coriolis Effect, described above, also acts to keep it. Because of these combined forces the layer of oceanward-flowing fresher water which tends to overflow the heavier inward-flowing ocean water is thicker or deeper on the western side of the Bay.

Daily and seasonal isohaline movements are fairly constant or regular—and reasonably predictable. The entire Chesapeake system and its

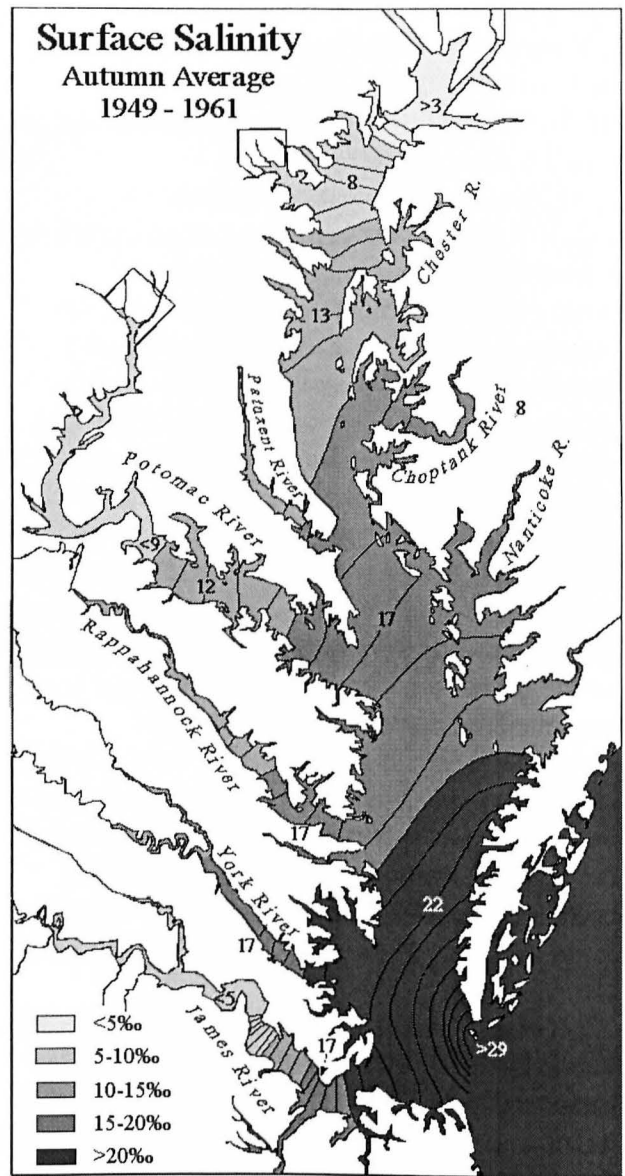


Figure 10. Distribution of average autumnal isohalines during the years 1949 to 1961.

Biota, are acclimated and attuned to them. But the system and its normal salinity regime are altered dramatically when higher-than-normal amounts of precipitation (rain, ice or snowfall) occur over large portions of the drainage basin of the Bay, especially in the upper watersheds of the major tributaries. Wet years (with prolonged periods of such higher precipitation) produce higher freshwater inflows from affected rivers, and the waters of differing salinity move further oceanward than normal. Components of the Biota capable of surviving such salinity shifts (freshets) for shorter periods of time, but not long ones, are often adversely affected.

Conversely, persistent drought conditions over large portions of the Chesapeake Basin reduce the fresh water inflows from the adjacent land masses and waters of higher salinity move further upstream. Elements of the Biota are also affected and motile organisms “preferring” higher salinity waters frequently move upstream in response to such upstream movements of higher salinity waters.

As examples, in June of 1972 Tropical Storm Agnes, the extremely persistent remnant of Hurricane Agnes, dropped great quantities of rain into the upland (mountainous) headwaters of the James, Potomac and Susquehanna in sequence as she moved northward. Peak river flows were measured on 22-24 June. The mainstem of the Chesapeake became fresh southward (oceanward) all the way to the latitude of Annapolis, MD for the first time in over 100 years. Similarly, markedly lowered salinities occurred in the James and Potomac rivers, and other tributaries of the Bay affected by the extremely high rainfall inland. Salinities remained depressed for a significant period of time—almost two months. Populations of plants and animals, physiologically dependent upon saltier waters, were subsequently “damaged” in the areas of the Bay and its tributaries thus affected. In many parts of the system large numbers of oysters on oyster beds (reef remnants) were killed, as happens in such instances to immobile (or “fixed”) animals and plants on or in the bottom—i.e., the **benthos**. (Some locations were officially declared economic disaster areas and financial relief was made available by government.) In the higher salinity waters of the lower Chesapeake and its tributaries, populations of the oyster drills (shellfish-boring and eating snails), *Urosalpinx cinerea* and *Eupleura caudata*, were significantly reduced.¹

In the James River, the downstream limit of freshwater (salinity of 0.5 ‰) usually is around the mouth of the Chickahominy River (Figure 1). During the prolonged and severe drought period

of the 1960's water containing measurable sea salts extended upriver to the City of Hopewell causing consternation to the officials at the water works of that city and allowing motile salinity-tolerant animals and phytoplankton to move further up the James River than normal.

Other Salinity Effects on the Biota

Aquatic organisms—plant and animal (planktonic, nektonic and pelagic alike)—are physiologically attuned to the amounts of mineral salts (“the salinity”) contained in the waters in which they live. The distribution of salinity in the water masses of the Bay (and in the sediments beneath them) affects distribution and abundance of all organisms, including those on or in the bottom (benthic organisms). It also determines, in large measure, whether they fare well or poorly wherever they may occur. In the few examples of the effects of floods (high flows) and droughts (low flows) previously discussed, the impacts of the salinity distribution on the Biota have been illustrated. These effects are compounded when the diseases and predators acting on the various species are themselves affected by alterations in the Bay's salinity regime. For example, Chesapeake oysters (*Crassostrea virginica*) can survive in waters of lower salinity—as low as 5.0 ‰—than can the boring snails, *Urosalpinx* and *Eupleura*, which eat them. Oysters can also survive and thrive in lower salinity waters than the microorganisms which cause significant oyster diseases (MSX and Dermo). During prolonged droughts, the salinity of the water around oyster beds becomes higher. When this occurs, these predatory snails are able to reach and attack oyster populations denied them during periods of lower salinity. Also, these oyster populations, normally protected from MSX and Dermo disease by salinities lower than these micro-organisms can tolerate, are attacked, weakened and many are killed during prolonged dry periods when the salinity of Bay waters is abnormally high.

¹ By 1998 they seemed to be returning to their “normal” haunts. Thus, the “dampening” effects of Agnes on these two species of predatory snails lasted some 18 years.

Climate and Weather

GENERAL

The term “weather” applies to meteorological happenings over a short span of time (i.e. hours or days) and/or over a relatively small geographical area. Consistent or characteristic weather patterns covering a significant geographical area and span of time are considered its climate.

Energy from the sun (measured in photons) is the primary weather and climate maker on Earth. The spatial relationship (distance and angle of inclination) between the particular location (spot) of interest on the surface of the Earth and the Sun is important. Any intervening elements in Earth’s atmosphere such as clouds, haze, precipitation, volcanic dust, sand, natural and manmade smoke and chemical smog, and other elements affecting the atmosphere’s transparency to the Sun’s rays will also affect the amount of photons (light energy) reaching that spot. The number of photons impinging on the atmosphere, its contents and on the surface of Earth near the region of interest determines patterns of atmospheric temperature, insolation (effective energy from the Sun), humidity, precipitation, winds, evaporation and other aspects of weather (and climate). The topography of Earth’s surface in any particular location, as well as the nature of the exposed surface there, including whether it is covered by water, herbage and foliage, bare earth (sand or soil), rock, roadways, snow, ice, or water also influences local and regional weather patterns.

Astronomical factors affect meteorological phenomena as well. For example, movements of Earth as it rotates (on its own axis), tilts, and wobbles in its elliptical orbit (now nearer—now farther) around the Sun affect the amount of sunlight (photons) impinging on Earth’s surface (and atmosphere) at any one locality, giving rise to seasonal changes in patterns of weather and climate. Due to Earth’s tilt its Northern Hemisphere receives more direct sunlight during the part of the year called summer and less direct sunlight in that part called winter: hence, atmospheric temperatures there are warmer in summer and cooler in winter. (The converse prevails in the Southern Hemisphere where the seasons are reversed, as Earth moves in relation to

the Sun.) Additionally, Earth is nearest the Sun in January and farthest in July, hence the Southern Hemisphere receives more solar energy during its summer than does the Northern Hemisphere.

MODERN WEATHER AND CLIMATE

The Chesapeake drainage basin, including its tributaries and the mainstem of the Bay extend northward over some 6 degrees of latitude of Earth’s surface (i.e. 360 nautical miles, 414 statute miles, 667 kilometers). This is a considerable distance in meteorological terms. It is not unusual for weather prevailing in the “Leatherstocking District” or Finger Lakes region of central (“upstate”) New York State, around the upper reaches of the North Branch of the Susquehanna River north of Binghamton, N.Y. (Fig. 2) to be considerably different from that south of the Virginia’s James River (sometimes called Southside Virginia), almost 400 miles away. Generally, summers begin earlier in Southside Virginia, where they are also hotter and more humid, and last longer. As well, winter weather begins later, and winters are generally milder and shorter around the southern part of the Chesapeake Basin. Around New York’s Finger Lakes region in the upper Susquehanna drainage (its’ North Branch) and nearby Great Lakes Erie and Ontario snowfall may begin as early as October (normally it begins to fly in November). Generally, in that part of New York state snowfall lasts longer [until mid-March (sometimes as late as mid-April)] and is much heavier than around the Chesapeake.

Circulatory movements of the ocean of air (the atmosphere) above the Chesapeake (the high and low pressure systems and the jet stream above) are important determiners of Chesapeake weather patterns and of the regional climate in the Chesapeake Basin. Normally, the prevailing atmospheric movements (wind currents) near Earth’s surface in our latitude are from west to east, as a result of the equator-to-pole transfer of thermal energy on an Earth that rotates from west to east. Changing weather patterns move with them. Consequently, most “weather” approaches the Chesapeake Bay, as well as its tributaries, from the west.

Semitropical air (warm fronts) normally approaches from the southwest: Canadian air (boreal—cold fronts) from the northwest. Occasionally, pressure systems bring wind (and weather changes) from other directions such as the northeast off of the North Atlantic (nor'easters) or southeast (hurricanes or, more frequently, their remnants—tropical storms) from the southerly reaches of the North Atlantic. Such strong storms usually arise above warmer tropical (equatorial) waters of the Atlantic or its daughters, the Caribbean Sea and the Gulf of Mexico. They, and nor'easters, are frequently violent and cause much erosion of "weather" shores along the Seaside of the Eastern Shore and southward along Virginia Beach and North Carolina's Outer Banks and nearby exposed shores, and in the Bay and its tributaries. Heavy rains from such storms cause flooding, especially upland, and—increased erosion and sedimentation in the Chesapeake and the tidal reaches of its tributary rivers and streams. The tropical storm remnants of Hurricanes Camille in 1969 and Agnes in 1972 brought great floods of freshwater (freshets) into the Chesapeake basin from upland drainage and caused much erosion in the upper reaches of the tributaries. Resulting sedimentation caused considerable "damage" to the Bay's benthic biota. These freshets also forced changes in the distribution of floating (planktonic), swimming (nektonic) and benthonic (bottom-dwelling) plants and/or animals.

The, sometimes, massive amounts of fresh water introduced into the tidal Chesapeake by such storms from upland can make great changes in salinity distribution patterns in Bay waters as described above. However, they generally have little effect on the level (height) of the tidal waters very far below the fall-lines of the affected tributaries. The distance over which their effects on water level are felt depends, of course, upon the volume of water dropped in the mountain and piedmont drainage. The total volume of water in the *estuarine portions* of the tidal tributaries is so great that, except for the "flood surge" in the upper coastal plain reaches just below the fall lines resulting from up-river floods (which diminishes relatively rapidly as it rushes over the falls), there is little effect on the level of the water in most of

the tidal portion of the affected tributary below the falls.

On the other hand, wind-driven increases in water level—surges resulting from the high winds of hurricanes and tropical storms, passing along-shore or across-shore (directly or obliquely), called storm surges, can cause great damage to the works of nature and man in the Chesapeake system. From time to time hurricanes or tropical storms passing nearby offshore can cause significant water level changes in which water piles up in the Upper Bay when the wind is from the south or in the lower Bay when winds are from the north. Local flooding can result. For example, Hurricane (later Tropical Storm and then low-grade Hurricane) Dennis caused flooding in Virginia's lower Bay when its winds blew much water down-Bay from the north as it first brushed (and later recurved and crossed) the outer banks of North Carolina in August of 1999. Conversely, the water level in the northern part of the Bay was lower than normal. Strong northeasters can cause local coastal flooding, especially if they coincide with high tides. The notorious Ash Wednesday storm of 1962 was such a Nor'easter. Abnormal weather events usually cause far greater changes in erosion and scouring and sedimentation than normal weather patterns. As described above with the effects of Hurricane Agnes on oyster drills, some Biota may be significantly disrupted as well. Most, however, recover relatively quickly since Chesapeake species have become well-adapted to the vagaries of Bay weather over the seven or so millenia of its evolution.

It is now apparent that weather over the Virginian Sea region of the North Atlantic affects the survival of finfish and blue crab larvae in offshore waters. Therefore, adverse weather there can affect the success of their year classes.

ANCIENT WEATHER AND CLIMATE

During the last ice age of the late Pleistocene Epoch (the Wisconsinan Ice Age) when the Laurentian Ice Cap of that period extended southward into the future Susquehanna River basin (see Fig. 3) the weather and climate were much colder than today. Studies of the distribution of fossil pollen during that ancient period indicate that

atmospheric conditions over the future Chesapeake basin were moister and cooler (Dent 1995). Precipitation was some 25% greater (especially snowfall in winter) and average air temperatures during July were 5°F lower than those today.

These conditions persisted into the early Holocene Epoch even after the Wisconsin Ice Cap had begun its long retreat northward. They affected most, probably all elements of the terrestrial Biota, including humans, and also most of the aquatic plants and animals of the times that lived around and in the Chesapeake as it evolved and “settled” into its present form. Weather and climate conditions prevailing during the last days of the Wisconsin Ice Age as the ice cap melted and meteorological conditions changed from subarctic to boreal to temperate) undoubtedly influenced the movements and pre-Contact distribution of aboriginal humans into and around the changing Chesapeake Basin.

Temperature Effects

Among the other important natural factors affecting the estuarine environment and biota is temperature—temperature of the water and of the air above it. During summer, the temperature of ocean water dominates that of the water in the lower Bay, especially the deeper, saltier layer. However, much of the Bay and its tributaries is shallow, averaging less than 27 feet (6.4 m) in depth, including the channels. Excluding the channels, it is much shallower, especially in the upper reaches of the Bay and its tributaries.¹ In many tributaries of the Chesapeake (most of which have a larger proportion of shallow to deep waters than the Bay, itself) shallow waters predominate in their estuarine reaches and in them effects of air temperature and insolation are even more pronounced. Therefore, air temperature is a significant factor in controlling the temperature of much of the water in the Bay and its tributaries.

Sunlight (insolation) dominates air and water temperatures during the day, especially in summer.

¹ In the lower Bay [up to 80 km (43.7 mi) from the mouth -- at about the latitude of the Potomac] 80% of the mainstem of the Bay is deeper than 5.5 m (18.0 ft.) while 75% is deeper than 6.5 m (21.3 ft).

Shallow and surface waters are warmest then. At night the water at the surface and in the shallows waters cool with the atmosphere. The absence of sunlight also affects both air and surface and near-surface water temperatures. Both are cooler on cloudy (or foggy) days than on bright ones. Thus, the water temperatures of the Chesapeake are attuned to variations in the distribution of sunlight. During overcast nights the heat loss from surface waters is lessened due to retention and reradiation of long-wave radiation into them. On clear nights long-wave radiation (heat) is lost to the atmosphere thus allowing surface waters to cool more.

As described more fully above, winter brings a reduction of insolation due to the position of the Chesapeake drainage basin on the northern hemisphere in relation to the Sun. During deep winter, the temperatures of the cooler waters from the rivers and from land run-off dominate much of the fresher water masses upstream and especially the shallow ones and at the surface of the mainstem of the Bay. Deeper Bay waters continue to be dominated by the temperature of inflowing oceanic waters which do not freeze. Occasionally, the surface waters of the Bay, or large portions thereof (especially in the less-saline portions of the shallows), freeze over during prolonged periods of cold weather over the Basin.

Animals and plants deal with the unfavorably colder water temperatures of winter in different ways. For example, blue crabs move into deeper waters and bury into the mud along the sides of channels in a sort of hibernation. While buried there and dormant they are easily captured by toothed dredges; the basis of the winter blue crab dredge fishery. Unfortunately, most of the adult blue crabs hibernating in the higher-salinity waters of the lower Bay are berried (i.e. carrying fertilized eggs attached to the swimmerets under their abdominal flaps—“pregnant”) females. Hence, winter dredging for hard crabs captures not only adult females but the developing larvae usually attached to them.

Many larger adult finfishes seek the warmer waters of the ocean to overwinter, especially those that spawn at sea such as Atlantic Menhaden (*Brevoortia tyrannus*), Spot (*Leiostomus xanthurus*), Atlantic Croaker (*Micropogonias*

undulatus) and Weakfish (*Cynoscion regalis*). Striped bass (*Morone saxatilis*) and some other large finfishes, normally remaining in the estuary in winter, congregate in deep holes where the water does not freeze and enter a semi-lethargic to lethargic state. Such highly-concentrated and semi-dormant animals are easily captured en masse by trawls and gill nets. Also, cross-infection by viruses, bacteria, microfungi and other infectious micro-organisms within densely packed (“compressed”) host populations may act to spread diseases during winter.

Other mobile animals that remain in the Bay and its tributaries simply move into deeper waters. But, some resident species bury themselves in the bottom mud as do Mummichogs (*Fundulus heteroclitus*), Sheepshead Minnows (*Cyprinodon variegatus*), and other smaller, shallow-water species.

Among multicellular plants the growth of Submerged Aquatic Vegetation (SAV) slows in winter as does that of wetland vegetation.

In winter, estuarine waters are usually clearer more transparent to light because phyto- and zooplankton are much reduced. Phytoplanktonic species encyst or entomb themselves in the mud.

Like salinity, temperature appears to play a significant role in the life-cycles of some disease-causing organisms. For example, higher than normal water temperatures in winter appear to favor survival and lethality of the microparasite that causes Dermo-disease of oysters. Coupled with higher-than-normal salinities in spring and/or summer, its damaging effects on infected oysters can be devastating.

Because they have become adapted to it over time most native estuarine animals and plants can tolerate the normal temperature regime of the Bay quite well. However, during extremely cold winters icing in surface and shallow waters can cause damage to exposed elements of the Biota. Under circumstances of prolonged periods of icing, oysters have been killed, especially those on the intertidal surfaces of once-prominent, surface-exposed oyster reefs. Grasses and other organisms in shallows have been likewise damaged.

Not only does cold winter weather affect animals of the Bay by “slowing them down” due to

decreased rates of metabolism, but so do extremely high water temperatures frequently prevailing in deep summer. Normally, many animals living in shallow waters and sediments enter into a state of dormancy or semi-dormancy in the “high season” of August. The process is termed *aestivation* by some.

Oxygen Requirements and Deficiencies

Lack of dissolved oxygen (DO) in certain Bay waters has received public attention in recent years.

Oxygen (O₂) is essential to most estuarine/marine biota and important in many natural chemical processes. Estuarine scientists use the terms Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) to describe the amount and rate that living biota and chemical activities (such as decomposition) consume oxygen. When either BOD or COD, or both, begin to require more O₂ than the system can produce, the condition known as hypoxia (low oxygen) begins and, if it persists sufficiently long, anoxia (where the water contains no oxygen) develops.

Most estuarine and coastal ocean waters carry sufficient dissolved oxygen to support their plants and animals, and other biota, most of the time. Under such conditions all BOD and COD requirements can be met. But, at times dissolved O₂ becomes scarce and biota suffers.

Most dissolved oxygen in estuarine and oceanic waters comes from the atmosphere across the air/water interface. Normally, lesser amounts are produced by plants through photosynthesis which, requiring light, varies according to available sunlight. When it is dark, plants consume oxygen, instead of producing it and produce the waste gas, carbon dioxide (CO₂). Animals do so all of the time—use O₂ and release CO₂.

The amount of atmospheric oxygen in the water column varies with the rate of absorption of O₂ by the surface waters at the air/water interface. Molecular diffusion occurs at all times but the rate of mixing and the amount of O₂ in the water column is affected most markedly by the turbulent

(mixing) action of wind and waves and other circulatory phenomena. Turbulent waters normally carry more O₂.

Generally, the closer to the surface any “parcel” of water is, the greater its dissolved oxygen (DO) load—up to the limits of absorption. Surface waters usually bear more oxygen than deeper waters which are farther away from the air/water interface. Absorption of oxygen molecules varies with water temperature and with salinity. Colder water normally absorbs and carries more O₂ than does warmer water. Both lower salinity waters and turbulent waters also absorb and carry more O₂.

As a consequence, conditions of low dissolved oxygen (hypoxia) usually occur in deeper and quieter water and at night—or when levels of sunlight are too low to support photosynthesis. Much recent concern over low oxygen and no oxygen (anoxia) in the Bay revolves around the deeper (channel) waters of its mainstem which have been known to experience hypoxic, even anoxic conditions, most notably in summer, *for decades*—probably much longer. Such conditions frequently develop during warmer periods in the deeper waters at the mouths of the Potomac, Rappahannock and York Rivers, for example. There, the problem is partially due to stagnation developing in the deep pools behind the “sills”—subsurface ridges or bars caused by benthic sedimentation that extend across their mouths.

In all of the deeper, poorly-circulating, darker (with less photosynthesis) waters of the Bay’s mainstem and its major tributaries, conditions of stagnation worsen as summer progresses and

freshwater inflow from the tributaries decreases, vertical-mixing between the layers decreases and the deeper water masses become still. Under such conditions mixing between the better-oxygenated upper layers, the more poorly oxygenated deeper, saltier layers decreases and the waters of the lower layers become deoxygenated due to continuing BOD and COD. In those lower layers, animals and plants—especially planktonic microorganisms trapped there—die, decompose and exacerbate the situation. These deeper waters frequently become anoxic for long periods of time and cannot support most oxygen-requiring life.

Temporary hypoxia and anoxia can develop in shallow waters when conditions deteriorate. Consequently fragile, oxygen-sensitive fish, such as Menhaden, are frequently killed in great numbers when their schools exhaust the dissolved O₂—usually during hot weather and at night. Sometimes massive fish kills result.

Destruction of forests and extensive agricultural and construction activities have increased the rate of sedimentation in the waters of the Bay. Excessive sedimentation may lead to hypoxia or anoxia. As well, point-source and non-point-source pollutants have added to the BOD and COD loads Bay waters must bear, consequently, the number and extent of occurrences of hypoxia, and even anoxia in some places and at some times, seem to have increased.

The Biota

Lots of sunlight, providing energy for photosynthesis, sustains plankton, submerged aquatic vegetation (SAV) and terrestrial plants in the water, on and in the bottom, in marshes (wetlands), lowlands and highlands. A generally mild climate assures long spawning and growing seasons. The location of the Bay-mouth near the southernmost edge of the **boreal** (colder) and the northernmost edge of the **subtropical** (warmer) Atlantic oceanic zoo-geographic regions or realms assures a dynamic mix of animals and plants in the

region. When these realms or zones move northward or southward for extended periods of the time, as they sometimes do in response to abnormally prolonged cooling or warming climatic conditions, changes in the Biota of the Chesapeake Bay and adjacent coastal waters occur.¹

¹ *When such alterations occur normally southern animals, such as Brown Pelicans (during prolonged warming period), or northern animals such as Harbor Seals (during prolonged cooling periods) appear in the Chesapeake. Such has been happening for a long time and appears “normal.”*

Nutrients from land, air, and sea, augmented greatly by man in recent times, affect the productivity of the Bay. Sedimentation, increasing, especially since Europeans arrived, is significant.

All of these chemical, geological and physical factors combine to make the Chesapeake Bay system a veritable protein and carbohydrate factory, based mostly upon local photosynthesis.

Therefore, some 2,700-2,800 species of plants and animals have been recorded from the Bay.¹ Certainly more will be discovered as biological research continues. The recent attention to the **dinoflagellates** related to fish diseases and kills will result in identification of a number of species of that “plant-animal” group not hitherto recorded as being part of the Bay Biota. Since each individual species of animal and plant in the Chesapeake is host to parasites and other **symbiotes**, the published Biota of the Bay surely will be doubled as they, too, are identified and described. And, there are thousands of other **macro-** and especially **micro-organisms** as yet undescribed. Science probably has not as yet discovered a tenth, or more, of the total number of species regularly or casually a part of the total Bay Biota.

It has been said that the aboriginal Indian name for Chesapeake, *Chesepiook*,² meant Great

Shellfish Bay. If so, the name undoubtedly referred to the extensive and massive reefs of oysters (and associates) growing upon ever-increasing foundations of shells left behind as successive generations set, lived, spawned and died. Other shell-bearing animals, such as mussels, barnacles and jingles added to the reefs. And in the bottom sediments all manner of hard-and soft-clams and other bivalves grew. All, especially the reef-building oysters, exerted strong influences on the Bay. Of all the Bay’s macro-invertebrates, the Eastern Oyster, *Crassostrea virginica*, could be considered to have been the dominant element of the Bay’s biota throughout most of the Chesapeake’s “mature” life—certainly up until about 200 years ago, when man’s depredations overcame the Bay’s oyster replacement abilities.

¹ *The commercially-important Blue Crab (Callinectes sapidus), Oyster (Crassostrea virginica) have already been mentioned as has the Atlantic Menhaden (Brevoortia tyrannus) in economically important finfish. There are some 267 finfishes in the Chesapeake Bay. Many of them are used for food and fun (sportfishing). See Murdy, Birdsong and Musick, cited in the Bibliography for more information on finfishes.*

² *Other spellings—attempts at Anglicization of an Indian word— exist.*

Humans

While humans are relatively recent additions to the Biota of the Bay region, they have become increasingly important to its well-being and its future. Recent archeological evidence indicates that **Paleo-Indians** [descendants of Asiatic peoples who crossed over onto the North American continent some 20,000 to 30,000 years ago (BP)] lived around the upper-Nottoway River [located on the southside of the James River around Courtland and Franklin, VA, and empties into the North Carolina Sound System (Figure 2)] by about 14,000 years BP (some 12,000 years BC). Earlier archeological work established them in the nearby James River basin around Jamestown Island by

12,000 BP and on the Potomac drainage about the same time. (Some archeologists are only confident of the 12,000 BP datings at this point.)

Comparison of paleo-archeological data with geological evidence established clearly that Asiatic-derived Paleo-Indians had arrived in the drainage basin of the future Chesapeake even before rising Atlantic waters had begun to intrude between future Capes Henry and Charles, and into the lowermost valleys of the **Wisconsinan** James and Susquehanna River Systems. After this great occurrence, some 7,500 years ago, many generations of American Indians watched the Bay being formed since it did not reach its present

approximate geographical proportions until around 3,000 BP to 2,500 BP.

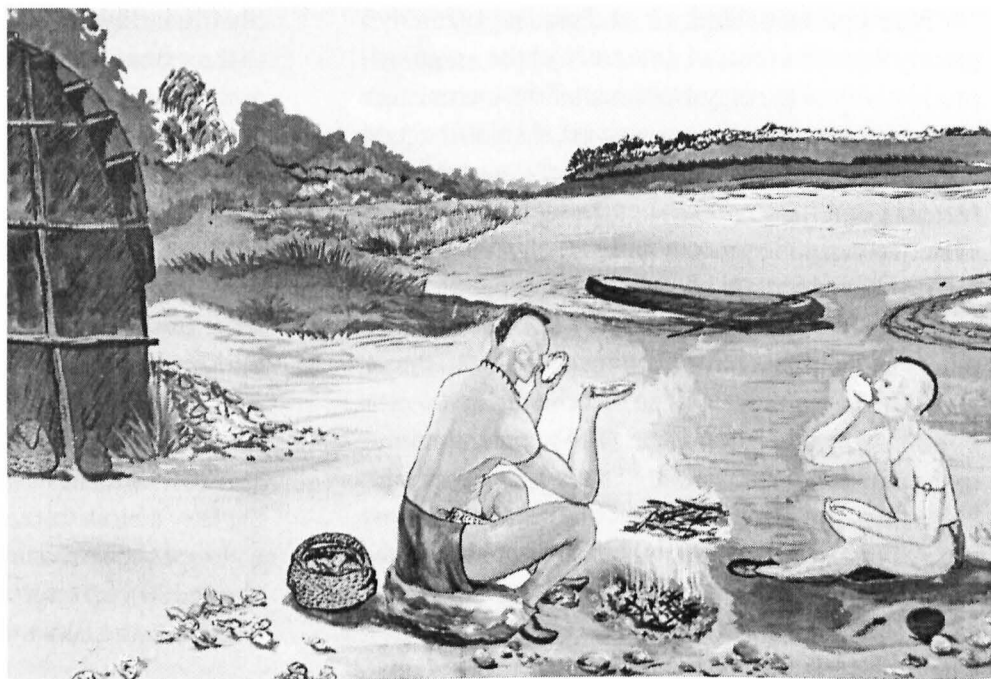
Some were forced to retreat upland from their hunting, camping or home sites on the Continental Shelf and in the valleys of the future James and Susquehanna systems as rising ocean waters advanced landward. During the ensuing four millennia, these semi-nomadic humans produced little effect upon their environment, despite their “slash and burn”

agriculture and “burn and kill” hunting practices. No one has yet reported direct evidence of their having killed mammoths and mastodons, However, they probably did help eliminate waning Ice Age mammal populations and other large vertebrates of the period.

Depending upon their technological capabilities, economic proclivities, and numbers, modern humans (*Homo sapiens*) are able to modify their environments more thoroughly and quickly than all other biotic entities. When Europeans arrived in the Chesapeake region in 1607 AD (about 400 BP), the resident aborigines were still at the Stone Age level of technology. Their weapons and other tools were made of stones and woods of various types. Of metallurgy, they knew little.¹ As well, their numbers were very few. Estimates indicate that some 36,000 or so lived in Virginia, Maryland and Delaware at the time (see footnote Table 1, p4).

Technological limitations and sociological factors combined with the small numbers of individuals limited the ability of Indians to disturb the land around the Chesapeake. They were unable to have much impact on the waters and resources of the system!

After the more technologically-advanced Europeans arrived in the region, the effects of man



upon the environment and resources of the Bay changed. At first, changes were slow to come, since the number of early immigrants was small and many died of various causes (such as warfare, bad drinking water, poor sanitation, and new disease epidemics) before adapting to their new environment. From 1607 AD to 1625 AD, some 7,500 colonists (and dependents) had arrived in the Virginia Colony. Only a few more than 1,000 had survived. The overall rate of attrition from all causes (including disease, starvation, warfare, accident, etc.) was an astounding 86%. Not until 1660 AD, some 50 years later, did their total numbers (including Africans and other non-Europeans) approximate the numbers of Indians present when Europeans first arrived at Jamestown. In the meantime, the number of Aborigines in the region probably had declined. But by 1700 AD (40 years later), the number of non-Aborigines had more than doubled. From then on, population growth in the two colonies (and succeeding political units) around the Bay was **exponential**. In 200 years, the number of individuals around the Bay totaled some 5,370,000.² Today, many cities and counties around the Chesapeake have more individuals in them than the total numbers of Indians living in the entire Bay region when European settlement began.

¹ Copper ornaments were, however, not uncommon.

² Virginia and Maryland.

The number of people living around the Chesapeake and its tributaries below Pennsylvania was predicted to be above 8 million by 2000 AD by Culliton et al.³

In the meantime, especially in the last two centuries, man's technological ability to modify the environment and to extract and reduce its resources has increased markedly. During that time, we have made profound inroads into its renewable and non-renewable resources, and wrought great changes in its geomorphology (i.e. shorelines, wetlands, shallows and channels) by bulkheading, filling and dredging, and reduced the quality of the waters of the Chesapeake and its tributaries. We have also added many contaminants unknown in kind (many foreign chemical compounds) or quantity to the Bay and its biota before they were introduced.

We will soon in 2007 celebrate 400 years since European man arrived here in 1607 AD. If the Chesapeake is to continue pleasant and useful for another four centuries, man must learn to do more with less and, especially, to cause fewer deleterious effects.

³ *We should be able to determine from the most recent census (2001) whether this prediction by Culliton et al. (1990) was correct.*

Will we be up to it?

Suggested Reading List

Much has been written about the Chesapeake Bay. Undoubtedly, more than any other estuary in the United States, perhaps the World. For many years, VIMS maintained a Chesapeake Bay Bibliography and the libraries of archival scientific and educational organizations around the Bay contain many interesting, instructive and useful items. Some of the vast body of literature, scientific, popular and otherwise, can now be accessed via computer. In the meantime, a short list of highly readable and instructive references may be useful.

- Collings, F. d'A. 1988. *The Discovery of the Chesapeake Bay. An Account of the Explorations of Captain John Smith in the Year 1608.* With illustrations by Leonard Vosburgh. ii-59. Chesapeake Bay Maritime Museum, Navy Point, P.O. Box 636, St. Michaels, MD 21663
- Curtin, Phillip D. Grace S. Brush, Grace S. and George W. Fisher (Eds.). 2001. *Discovering the Chesapeake. The History of an Ecosystem.* The Johns Hopkins University Press, Baltimore and London. xiv-383.
- Davison, Steven G., Jay G. Merwin, Jr., John Capper, Garret Power, Frank R. Shivers, Jr. 1997. *Chesapeake Waters: Four Centuries of Controversy, Concern and Legislation,* (Second Edition) xiii-272. Tidewater Publishers, Centerville, MD 21617.
- Dent, Richard J., Jr. 1995. *Chesapeake Prehistory, Old Traditions, New Directions.* Plenum Press. New York and London.
- Duke, Maurice. 1993. Foreword by John Morton Barber. *Chesapeake Bay Voices: Narrative from Four Centuries.* xv-244. The Dietz Press, Richmond, VA.
- Hargis, William J., Jr. and Shirley O. Sterling. 2003. *A Chesapeake Bibliography.* 53 pp. Special Publication of the Virginia Institute of Marine Science of the College of William and Mary. P.O. Box 1346, Gloucester Point, VA 23062.
- Hays, Anne M. and Harriet R. Hazelton. 1975. Illustrations by Mary J. Hazleton. *Chesapeake Kaleidoscope.* viii-148. Tidewater Publishers, Centerville, MD, 21617.
- Horton, Tom. 1987. *Bay Country: Reflections on the Chesapeake.* xiv-214. The Johns Hopkins University Press, Baltimore, MD 21211. (Reprinted by Ticknor and Fields, New York).
- Horton, Tom and William M. Eichbaum. 1991. *Turning the Tide: Saving the Chesapeake Bay.* xxiv-324. Published by Island Press, Suite 300, 1718 Connecticut Avenue, NW, Washington, D.C. 20009 for the Chesapeake Bay Foundation.
- Klingel, Gilbert C. 1951. *The Bay. A Naturalist Discovers a Universe of Life Above and Below the Chesapeake.* With illustrations by Natalie Harlan Davis. viii-278. Dodd, Mead and Company, N.Y.
- Lippson, Alice Jane and Robert L. Lippson. 1997. Illustrations by Alice Jane Lippson. *Life in Chesapeake Bay. An Illustrated Guide to the Fishes, Invertebrates, Plants, Birds and Other animals of Bays and Inlets from Cape Cod to Cape Hatteras.* (Second Edition) x-294. The Johns Hopkins University Press. 2715 North Charles Street, Baltimore, MD 21218.
- Lucy, Jon, Terry Ritter, and Jerry La Rue. 1991. *The Chesapeake Weather: a Boating Guide to Weather.* VIMS Educational Series No. 25. Virginia Institute of Marine Science, Gloucester Point, VA 23062. (A cooperative Publication of VIMS Sea Grant Marine Advisory Services and NOAA National Weather Service). 22 pp.
- McCary, Ben C. 1957. Pp 1-93. *Indians in Seventeenth Century Virginia.* University of Virginia, Charlottesville, VA.
- McErlean, Andrew J. 1972. Catherine Kerby and Marvin L. Wass (Eds.). *Biota of the Chesapeake Bay.* 197 pp. Published for the Chesapeake Research Consortium by Chesapeake Science. (Chesapeake Science, Dec. 1972, Vol. 13 - Supplement. Chesapeake Research Consortium).
- Miers, Earl Schenck. 1967. *The Drowned River, The Story of Chesapeake Bay.* 30 pp. Friends of the Curtis Paper Company, Newark, Delaware.

- Murdy, Edward O., Ray S. Birdsong and John A. Musick. 1997. *Fishes of Chesapeake Bay*. xi-324. Smithsonian Institution Press, Washington and London.
- Poag, C. Wylie. 1998. *The Chesapeake Bay Bolide Impact: A New View of Coastal Plan Evolution*. U.S. Geological survey Fact Sheet (FS 049-98), May, 1998. 2pp.
- Poag, C. Wylie. 1999. *Chesapeake Invader: Discovering America's Giant Meteorite Crater*. Princeton University Press, 41 William Street, Princeton, New Jersey 08540. xii-183.
- Reshetiloff, Kathryn (Editor). 1997. Illustrations by Sandra Janniche. *Chesapeake Bay: Introduction to an Ecosystem*. 29 pp. Chesapeake Bay Program. Printed by the Environmental Protection Agency. EPA 903-12-97-024, September 1997.
- Schubel, Jerry R. 1981. *The Living Chesapeake*. x-111. The Johns Hopkins University Press, Baltimore, MD, 21218.
- Smith, John. 1624. *A General History of Virginia, New England and the Summer Isles*. xi-248. First Printed in 1624 by I.D. and I.H. for Michael Sparks in London. Reprinted recently (1998?) by The New England and Virginia Company, P.O. Box 8511, Salem, MA 01971.
- Stranahan, Susan Q. 1993. *Susquehanna, River of Dreams*. 1-322. the Johns Hopkins University Press, Baltimore and London.
- Tate, Thad W. and David L. Ammerman (Eds.). 1979. *The Chesapeake in the Seventeenth Century. Essays on Anglo-American Society and Politics*. vii-310. Published for the Institute of Early American History and Culture at Williamsburg, VA. W. W. Norton and Co. Inc. 500 Fifth Avenue, N.Y., NY 10110.
- Tilp, Frederick. 1978. *This Was Potomac River*. (Second Edition with Corrections). xv-358, with Pictorial Supplement. Published by Frederick Tilp, 124 Quay Street, Box 680, Alexandria, VA.
- Tilp, Frederick. 1982. *The Chesapeake Bay of Yore: Mainly About the Rowing and Sailing Craft*. xi-148. Published by Frederick Tilp, 124 Quay Street, Box 680, Alexandria, VA 22313. Distribution by The Chesapeake Bay Foundation, Inc. Annapolis and Richmond.
- Tilp, Frederick and Fay Tilp. 1988. *Chesapeake: Fact, Fiction and Fun*. xvi-238. Heritage Books, Inc. 1540 E. Pointer Ride Place, Bowie, MD 20716.
- Warner, William W. 1976. (Drawings by Consuelo Hanks.) *Beautiful Swimmers. Watermen, Crabs and the Chesapeake Bay*. xiii-304. Little Brown and Company (Canada) Limited. Boston, MA.
- Wharton, James 1957. *The Bounty of the Chesapeake: Fishing in Colonial Virginia*. 78pp. Virginia 350th Anniversary Celebration, Williamsburg, VA. (Series now being reprinted by the University Press of Virginia. Charlottesville, VA.).
- White, Christopher P. 1989. (Drawings by Karen Teramura.) *Chesapeake Bay. Nature of the Estuary. A Field Guide*. ix-212. Tidewater Publishers, Centreville, MD 21617.
- Wilstach, Paul. 1929. *Tidewater Virginia*. 1-325. Tudor Publishing Co, New York.
- Wilstach, Paul. 1931. *Tidewater Maryland*. 1-383. Tudor Publishing Co., New York.
- Wilstach, Paul. 1937. *Potomac Landings*. 1-378. Tudor Publishing Co., New York.

Glossary

anoxia - the condition of no dissolved oxygen in the water.

aquifer - a water-bearing geological stratum (layer) of permeable rock, sand, or gravel.

artesian water - water which flows below the surface of the ground in the underground aquifers.

BP - before the present.

benthos - community or communities of organisms living on or in the bottom. Generally immotile or of limited motility or range. The term benthic is often used to refer to such organisms or assemblages.

boreal - of, relating to, or located in the northern biotic area, characterized especially by dominance of coniferous forests on land or cold subarctic water and associated animals or plants in the adjacent seas.

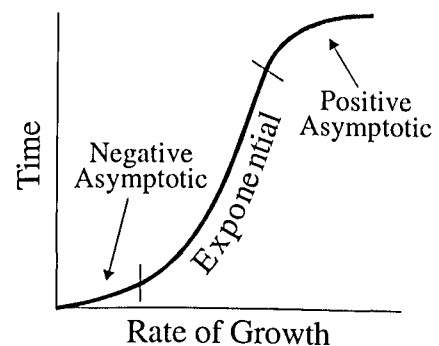
Coriolis Effect - The rotation of the Earth about its axis causes moving particles to behave in a way that can only be understood by adding a rotational dependent force. To an observer in space, a moving body would continue to move in a straight line unless the motion were acted upon by some other force. To an Earth-bound observer, however, this motion cannot be along a straight line because the reference frame is the rotating Earth. This is similar to the effect that would be experienced by an observer standing on a large turntable if an object moved over the turntable in a straight line relative to the "outside" world. An apparent deflection of the path of the moving object would be seen. If the turntable rotated counter-clockwise, the apparent deflection would be to the right of the direction of the moving object, relative to the observer fixed on the turntable. This remarkable effect is evident in the behavior of ocean, estuarine, and riverine (and atmospheric) currents. It is called the Coriolis force, named after Gustave-Gaspard Coriolis, a 19th-century French engineer and mathematician. For the Earth, horizontal deflections due to the rotational induced Coriolis force act on particles moving in any horizontal direction. There also are apparent vertical forces, but these are of minor importance to ocean currents. Because the Earth rotates from west to east about its axis, an observer in the Northern Hemisphere would notice a deflection of a moving body toward the right. In the Southern Hemisphere, this deflection would be toward the

left. At the equator there would be no apparent horizontal deflection.

dinoflagellate- any species of a plant order (*Dinoflagellata*) of chiefly marine planktonic, usually solitary, unicellular phytoflagellates that include luminescent ones, many species important in marine food chains, and some causing red tide, and which have been implicated by some in recent epidemics of ulcerations and in deaths of estuarine fishes, including Atlantic Menhaden—i.e. *Pfiesteriosis*, etc.

estuary - a more-or-less open (or semi-enclosed) coastal body of water body within which freshwater from the land (riverine) meets, mixes with, and dilutes the higher salinity water from the ocean. Brackish estuarine waters are decreasingly salty in the upstream direction and vice versa. The ocean tides are projected upstream to the fall lines.

exponential - the abruptly upward-trending "straight line" portion of a sigmoid curve. The sigmoid curve employed here appears thus:



The rate of human population growth was relatively very low for the entire period of Indian invasion, settlement and occupation of the Chesapeake Region (Table 1). It remained low through the first 50 years of European colonization (Tables 1 and 2). According to available census figures, numbers of Europeans and Africans (and, later, those from other large land masses) in the region were low until 1700 (Table 2). Growth during this early period could be conceived roughly as being negatively asymptotic. Since then, population growth has been exponential. If exponential growth continues and does not reach the positive asymptote ("fall-off"), the Chesapeake's early demise as a productive and pleasant environment will be assured!

geomorphology - a science that deals with the relief features of the earth or of another celestial body (such as the moon) and seeks a geological interpretation.

geochronology - the science dealing with establishing the age(s) of geological events, processes, approaches and artifacts.

Holocene - most recent of the two geological epochs that comprise the Quaternary Period, and the latest interval of the Earth's geologic history. The Holocene Epoch followed the Pleistocene Epoch, and constitutes the last 10,000 years to the present. It succeeded the last glacial stage of the much longer (several million years) Pleistocene and is characterized by relatively warm climatic conditions. It resulted from a period of "global warming" which, on average, has persisted for some 18,000 years since the Wisconsinan Ice Cap began to melt and recede toward more northerly latitudes.

hypoxia - condition of low dissolved oxygen in the water.

isohaline(s) - line(s) demarking water mass(es) of a particular salinity used by marine scientists to identify water masses according to the amounts of salt they contain.

macro-organism - an organism visible without a microscope.

micro-organism - an organism of microscopic or ultramicroscopic size, requiring magnification to see and/or study.

nekton - actively swimming pelagic organisms; nektonic - adjective.

Paleo-Indian - one of the early, prehistoric North and South American hunting people of Asian origin extant in the late Pleistocene Period (during or after the retreat of the last continental glacier).

point-source pollution - pollution that is released at the end of a pipe or other clearly identifiable point of entry. This contrasts with non-point-source pollution which comes from diffuse sources.

pelagic - organisms occurring in the water column.

pre-contact - the term used to indicate the time or condition before immigrants of western origin arrived in America and came into contact with the American Indians. (post-contact refers to the time or condition after they began to interact).

planimeter - an mathematical instrument for planar measuring the area of a (flat) figure by tracing its boundary lines. The simplest ones measure the length(s) of the line or lines being traced.

plankton - passively floating or weakly swimming animal and plant life of a body of water. planktonic - adjective.

saturation - when the dissolved O² levels are at the maximum possible at any particular water temperature.

statute mile - geographical unit of distance = 5,280 feet as opposed to a nautical mile, which is equal to one minute of arc of a great circle of earth or 6,076 or a little over 6,076 feet (6,076.11549 ft. to be exact).

stratified - to be arranged in layers—as used in estuarine science semistratified means partially layered.

subarctic - just below the Arctic Circle; hence next in rank geographically-speaking in terms of cold climate. The next coldest is boreal, followed by temperate. These are called climate zones based largely on prevailing atmospheric temperature by climatologists.

subtropical - of, relating to, or being the regions bordering on the tropical zone.

symbiosis - the intimate living together of two kinds (species) of organisms, especially if such association is of mutual advantage.

weather shore - the shore which generally receives most of the wind and therefore erodes most rapidly. This contrasts with "lee shore" - the shore that is most protected from prevailing winds, and thus tends to "build."

Wisconsinan - most recent Ice Age of Pleistocene time and deposits in North America. It was named for rock deposits studied in the state of Wisconsin. In North America, the last Ice Age is termed the Wisconsinan Ice Age; in Europe, the Würm. The Wisconsinan Ice Age persisted for some 122,000 years of the Pleistocene which itself persisted from about 1,640,000 BP to about 10,000 BP. As with other geological periods, times are approximate.