SALINITY IN PAMLICO SOUND, NORTH CAROLINA
A SPACE-TIME APPROACH

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Jonathan David Phillips. SALINITY IN PAMLICO SOUND, NORTH CAROLINA: A SPACE-TIME APPROACH. (Under the direction of Richard A. Stephenson) Department of Geography and Planning, April, 1982.

The Pamlico Sound estuarine system is a complex one, with human, physical, and biotic components. These components interact and are spatially linked with alterations of one component related to the others. The purpose of this study was to establish the temporal behavior of a physical component, salinity, and to relate this behavior to human and biotic components.

From 1948-1981 salinity levels showed evidence of a gradual long term declining trend throughout most of the study area. This trend is not explainable in terms of climatic variation or other factors. During the same time period, anthropic drainage activities increased dramatically in lands adjacent to the study area. The spatial variation in salinity trends was found to have an areal association with the level of anthropic drainage impact. Additionally, the salinity and drainage factors were related, temporally and spatially, to the spatial displacement of oysters. Oyster displacement is an example of the biotic responses that often accompany salinity changes. A functional relationship exists between estuarine salinity, land use in adjacent areas, and estuarine biota. Spatial linkages exist in that alterations of land by man-made drainage are related to salinity and biotic changes at other locations.

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CHAPTER ONE

INTRODUCTION

Estuaries where fresh water mixes with salt water are among the most dynamic, fragile, and productive areas on earth. These vital zones have considerable ecological, economic, recreational, and aesthetic value (see Clark, 1977; U.S. Department of Interior, 1970; U.S. Fish and Wildlife Service, 1970). The complexity and fragility of brackish estuaries associated with barrier islands is expressed within an environmental impact statement on barrier islands:

> . . . the brackish water, is extremely valuable as a fishery and for its production of vast quantities of seafood. With its protected waters, its recreational value is also undoubted, as these waters support numerous marinas and waterfront subdivisions. It must be remembered, however, that this brackish water is itself an ecosystem of finely-tuned associations of freshwater, saltwater transported nutrients and a variety of plant and animal species. The plants and animals are conditioned to and depend upon the natural ambient conditions, including the flux of salinity, the seasonal changes of temperature or dissolved oxygen, and, especially, the protection offered by the barrier islands from major storm winds and tides. These water bodies are fragile in that they do not require too serious an intrusion to upset the natural dynamic balance. (U.S. Department of Interior, 1979:99).

One such area is the Pamlico Sound in North Carolina. Intrusions, some serious, are currently having an impact on the area, and may be in danger of upsetting this "natural dynamic balance". The purpose of this study is to examine one such intrusion: Anthropic drainage of adjacent lands, its effects on salinity, a key factor in estuaries, and the environmental response to salinity changes.

Rapid change in salinity and other variables is the norm in estuaries. Mangelsdorf (1967) once estimated that summer salinity gradients in Chesapeake Bay were so local and transient that a precision of plus or minus 0.003 parts per thousand would be wasted unless location was specified to within 40 feet, time of sampling to within 90 seconds, and depth to within a quarter of an inch. Denman and Platt (1978:227) note that such natural dynamism is compounded by bad weather, costs, equipment failures and other factors:

> The net result is that a brute-force attack on the system, where we are armed with the ideal data set, is impossible. Rather, we must attempt through judicious experimental design and sampling to isolate certain processes or interactions for study.

The potential importance of the problems in the Pamlico area call for just such an approach.

Problem Statement

The objectives of this study are threefold: (1) To determine the spatial and temporal patterns of salinity in the western portion of Pamlico Sound, and its estuarine tributaries, (2) to document environmental response to salinity trends, and (3) to establish a functional relationship, in terms of spatial linkages, between estuarine salinity, environmental response, and land use of adjacent lands (specifically drainage). Land use in a watershed is linked to water quality via natural and man-made channels. Salinity and anthropic drainage may be said to be spatially linked if the variation in man-made channels is related to the variation in salinity of receiving waters.

Officials concerned with fisheries and environmental management in the coastal zone have for some time suspected a general long term decrease in salinity in western Pamlico Sound and the Pamlico and Neuse River estuaries. A relationship with drainage of nearby lowlands for agriculture and forestry has also been suspected, in addition to relationships between salinity and estuarine species such as shrimp and oysters. In 1981, for example, the North Carolina Assistant Secretary for Natural Resources reported to the State Water Conference that salinity in Pamlico Sound had been declining for 25 years as part of a call for more applied research in the region (Grigg, 1981). The North Carolina Water Quality Task Force in 1981 received a report on water problems in the state's estuaries from the North Carolina Office of Coastal Management (Schmidt, 1981). The study stated that a 10-mile downstream migration of oysters in the Pamlico River was apparently related to a declining salinity trend, and also noted a suspected salinity decline in the Neuse River. The report linked these phenomena to coastal area land drainage.

Sholar (1980) concluded in a North Carolina Division of Marine Fisheries report that there is evidence of a long term salinity decline in the Pamlico Sound area, possibly accompanied by a biological response. Another Division of Marine Fisheries official, James T. Brown, stated in 1978 that freshwater intrusion and declining salinities were a major problem in North Carolina estuaries because of adverse effects on commercial species (Doucette and Phillips, 1979:5-11).

Other observers have noted the possible problems, including salinity changes, related to man-made drainage activities in the Pamlico area. Heath (1975:75) stated in a U.S. Geological Survey Report that "the effect of runoff from the region (the Pamlico-Albemarle peninsula) on the quality of nearby estuarine waters, chiefly Albemarle and Pamlico Sounds, may be the most important problem posed by agricultural developments." The newsletter of the North Carolina Sea Grant program also indicated problems in estuaries posed by adjacent or upstream changes in land use. The director of the program, B.J. Copeland, observed that large-scale land use changes, such as drainage projects, pose the greatest current threat to the environmental quality of North Carolina estuaries (University of North Carolina Sea Grant, 1980).

Macro-scale studies of spatial linkages of major components of estuarine systems have focused on morphological variables rather than on relationships between anthropic, physical, and ecological factors. Research related to this study exist in three general forms: (1) systematic studies similar in focus but on a micro-scale of one small estuary, (2) general studies of salinity regimes in estuaries, and (3) studies of land use changes and anthropic drainage activities in eastern North Carolina.

The only previous attempt at a macro-scale investigation of salinity trends in Pamlico Sound is Sholar (1980). This report did not consider drainage impact, however, and presented no spatial analysis of salinity data. Sholar's study may be considered the springboard for this study.

The magnitude of the problems involving salinity and land use in the Pamlico area cannot be fully known for some time. It is clear at present, however, that there is recognition of problems and potential problems involving salinity, land use, and environmental quality in

Pamlico Sound and other estuaries. This study intends to define variables relevant to the problems indicated above.

Salinity as a Spatial Determinant

Salinity of water refers to the salt content of water, and is formally defined in this context as the total amount of dissolved seawater in parts per thousand (ppt) by weight when all the carbonate has been converted to oxide, the bromide and iodide to chloride, and all organic matter is completely oxidized (Gagliano, et al, 1970B:6). Salinity readings presented herein are in parts per thousand sodium chloride.

Salinity is related to the distribution, survival, health, and reproduction of estuarine organisms and has been called an "ecological master factor" (Kinne, 1966). Salinity has historically been used as an index to the ecology of the coastal zone (Gunter, 1961; Gagliano, et al, 1970B:6). Variations in the number, diversity, individual size, and spatial distribution of species have been linked to spatial and temporal variations in salinity with organisms affected by low, high, and unstable salinity (Gunter, 1956; 1961; Wells, 1961).

The critical role of salinity is now generally accepted as given by coastal area planners and managers. For example, a study on areas of environmental concern in North Carolina coastal areas cautions that changes in freshwater discharge that alter salinity patterns in the state's estuaries "will be reflected directly in the functioning of the estuary and this in turn will control the plant and animal populations in the system" (Thayer, 1975:64). This is also reflected in other treatments of coastal zone management (Clark, 1977).

More specifically, North Carolina Division of Marine Fisheries studies have noted the observed and potential effects of salinity changes on commercial species in western Pamlico Sound (Pate and Jones, 1980; Sholar, 1980). Numerous studies exist where salinity is used as an independent variable in studies of species distributions. Examples of such work within the area of interest include studies of fish distributions in the Neuse River (Keup and Bayless, 1964), macrobenthos in the Pamlico River (Tenore, 1970), and the epifauna of the Pamlico (Reed, 1978).

Salinity is also a key physical parameter in estuaries. Water density, specific gravity, conductivity, and temperature are all related to salinity. Salinity is thus a major factor in estuarine water circulation (Dyer, 1973). Salinity is also related to various other chemical components of estuarine waters. Oxygen depletion and occurrence of sedimentary phosphorus, for example, have both been linked to salinity in the Pamlico River (Davis, et al, 1978; Upchurch, 1972).

Because of its importance as an estuarine component, salinity is often used as a boundary criterion when delimiting regions for coastal area planning, management, and research. Clark (1977) recommends a salinity criterion in delimiting administrative and planning boundaries of coastal areas. Smith (1977) uses salinity as an indicator of the boundary of the estuary itself.

Salinity has implications for biological distributions and ecological functions in estuaries, determining in large measure the biogeography of the regions, and, by extension, man's use of these areas. When this is considered along with the role of salinity in water circulation and as a boundary criterion, it is clear that changes in salinity regimes have serious spatial ramifications.

Study Area

General description

The study area is located in the central coastal plain of North Carolina. The study area includes the following waters and their adjacent lands: Pamlico Sound west of the 75°50' west meridian, and the Pamlico River upstream to the U.S. 17 bridge at Washington, N.C., the Neuse River to the U.S. 17 bridge at New Bern, N.C., and the Pungo River at the U.S. 264 bridge at Leechville, N.C. The area is shown in Figure 1.

Delimitation of the area is based on physiography. The 75°50' west meridian coincides roughly with Bluff Shoal, which spans Pamlico Sound from Bluff Point to Ocracoke Island, dividing the sound into eastern and western portions. The upstream boundaries are at or near the points where the respective rivers widen, decrease noticeably in velocity, and have salinity levels high enough at least part of the year to support estuarine species.

Pamlico Sound is the largest body of water in North Carolina and the largest water body behind a barrier island system on the United States coast (National Oceanic and Atmospheric Administration, 1980:91). It is part of an interconnected system of North Carolina estuaries extending from the Virginia border to Beaufort, N.C., more than 130 miles to the south. It is nearly 100 miles from Washington at the head of the Pamlico River to Cape Hatteras at the easternmost boundary of the sound.

The study area was chosen because of the perceived declining salinity problem in the area, and the ecological, economic, recreational, and

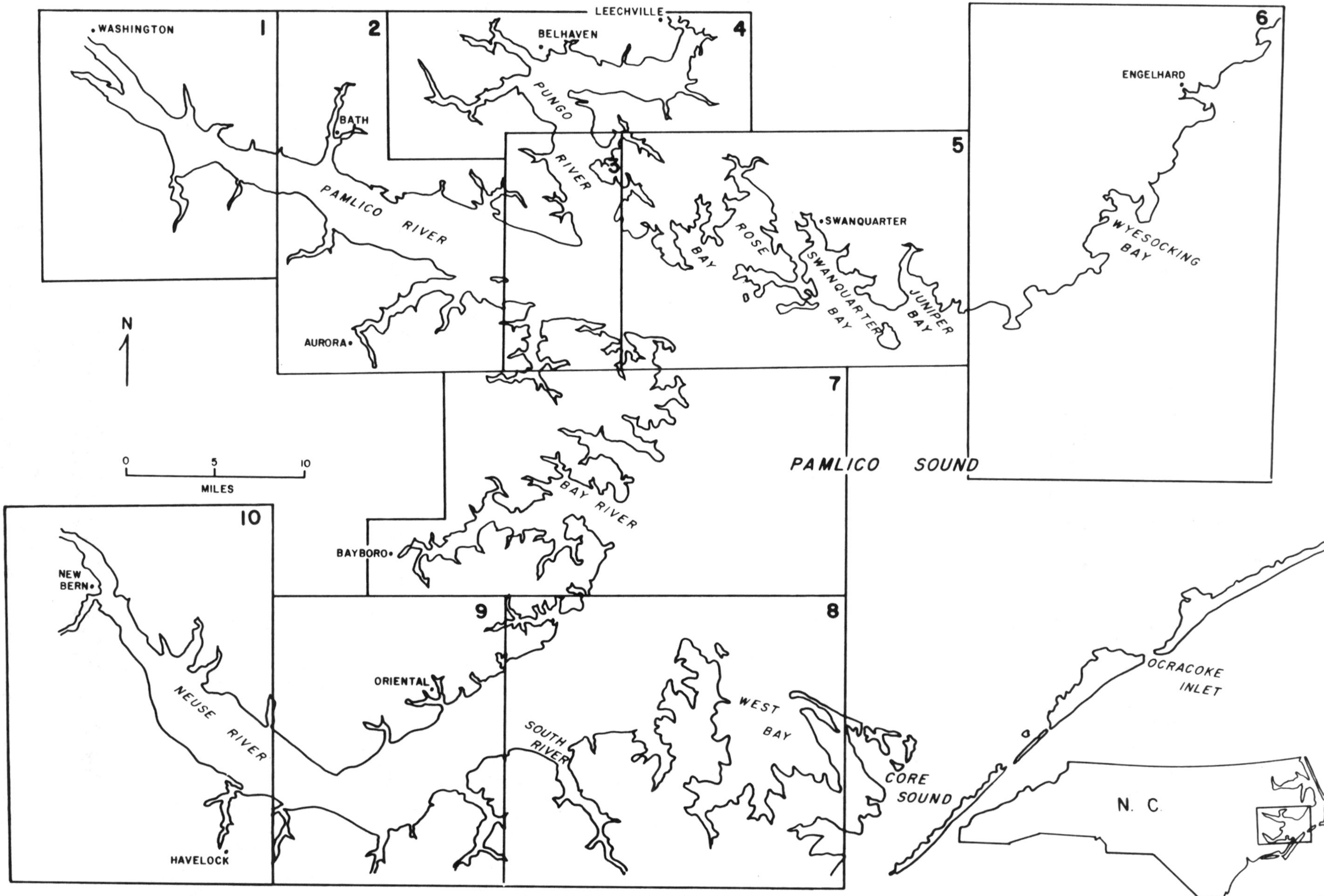

FIGURE 1: STUDY AREA

aesthetic importance of the area to North Carolinians.

One property of the system related to all the above benefits is the role of the estuary as a diverse and productive biological zone. Illustrative of this is the value of commercial fishing in the region. The Pamlico area is a nursery for shrimp, croaker, and other commercial species that spawn in the estuary and may be harvested in the estuary or at sea. Other species, such as oysters, crabs, eels, and brown shrimp, are harvested directly from the area. Catch statistics show the area leading North Carolina in brown shrimp, eel, and oyster production, and in the past Pamlico Sound has yielded more than 80 percent of the state's oysters (Chestnutt, 1951:155). Belhaven, on the Pungo River, is the largest single center for blue crab processing on the east coast. Commercial landings for Hyde, Beaufort, Pamlico, and Craven Counties, bordering the study area, totalled an estimated $23,578,424 in dockside value in 1979 (N.C. Division of Marine Fisheries, 1980). This represents approximately 47 percent of the dockside value reported for North Carolina in 1979.

Physical setting

The study area is in the South Atlantic Estuarine Region. This region is characterized by a wide continental shelf, contacting the Gulf Stream at its margins. A low, sediment-rich coastal plain is dissected by rivers, with drainage systems terminating in islands and salt marshes (U.S. Department of Interior, 1970:12). Pamlico Sound is in the southernmost portion of the "embayed" section of the Atlantic Coastal Plain, characterized by large drowned estuaries. The North Carolina coastal plain is underlain by an eastward-dipping monoclinal wedge of sediments deposited in the

Mid-Mesozoic era over basement of crystalline rock (Hardaway, 1980:12). The region is within the area commonly referred to as the outer coastal plain or tidewater region, a low-lying area averaging not more than 20 feet in elevation (Stuckey, 1965). The study area is astride several marine terraces of the Pleistocene age. The most significant of these features with respect to this study is the Suffolk Scarp, which separates the Pamlico Terrace from the Talbot Terrace to the west. East of the scarp, which has an elevation of about 25 feet, lies the lowest land with the poorest natural drainage (Stuckey, 1965).

According to the classification scheme developed by Pritchard (1967), Pamlico Sound is a bar-built estuary impounded behind the Outer Banks, a chain of barrier islands. The region also has characteristics of the drowned river valley estuary.

Hydrography

Surface waters within the study area are broad and shallow. Nautical charts show a maximum depth of 25 feet at mean low water with many areas less than five feet deep. Typical open-water depths in the upper rivers and bays is six to eight feet with 15 to 20 feet in the lower rivers and midsound areas. Nearshore depths are one to three feet. Shoaling is common with several major shoals all extending generally from the mainland toward Ocracoke Inlet: Bluff Shoal, tending north-south at the eastern edge of the study area; Middle Ground, extending southeasterly from Swan Quarter; and Brant Island Shoal, protruding from Goose Creek Island parallel to Middle Ground. Charts also indicate shoaling around most points and meanders in creeks and rivers, at tributary mouths, and in extensive areas around Point of Marsh. Navigation routes include a portion of the Atlantic Intracoastal Waterway. These routes typically follow shifting natural channels, and some dredged channels at sediment-rich creek mouths and in intermittent stretches of the Neuse and Pamlico Rivers.

Long fetches result in frequent choppy water. Pamlico Sound proper is approximately 65 miles at its longest and 25 miles at its widest with additional fetches across major tributary reaches and adjacent sounds. The entire area is well-mixed in general and is considered wind-dominated with respect to short-term water levels and circulation (Giese, et al, 1979:71-122). Freshwater input is the major long term determinant of water levels and circulation in the study area. The chief sources are the Neuse-Trent and Tar-Pamlico (the Tar River becomes the Pamlico River at Washington, N.C.) River systems. Albemarle Sound also drains into Pamlico Sound via Roanoke and Croatan Sounds. Including Albemarle Sound and its tributaries, Pamlico Sound receives drainage from nearly 31,000 square miles. The Neuse-Trent and Tar-Pamlico systems combined drain 12,500 square miles--about one fifth of the land area of North Carolina (Giese, et al, 1979:71). Numerous small, lateral tributaries supply additional fresh water to the sound.

The major ocean connection in western Pamlico Sound is Ocracoke Inlet. To the northeast are Hatteras and Oregon Inlets. All are narrow, shifting outlets. Smaller still are several minor inlets connecting Core Sound to the Atlantic Ocean south of the study area. Due to these restrictive connections and the protection of the islands, nautical charts indicate a diurnal lunar tidal range of less than half a foot throughout most of the region.

Socioeconomic Setting

The counties surrounding the Pamlico area are predominantly rural. New Bern, Washington, and Havelock are the only settlements with 1980 census populations greater than 3,000. These are also the only sites with significant industry with the exception of a large phosphate mining and processing operation in the vicinity of Aurora. Dominant economic activities include agriculture (corn, soybeans, tobacco, hogs), forest products, commercial fishing, and tourism. Although portions of the area are relatively undeveloped due both to their remoteness and to physical constraints, there are densely-settled areas of recreational and retirement housing along numerous waterfront areas. Per capita income has historically been lower in the area than in the rest of North Carolina, and until the 1970s the region experienced a net loss of population.

Methodology

The research objectives required collection of three kinds of data for the post World War II time period: salinity data, information relating to environmental responses to salinity, and data on land use and anthropic drainage activities.

Salinity data for the study area are among the best for any area of North Carolina. Very little salinity data were gathered before 1948, however, and data gathered since then is derived from an uncoordinated hodgepodge of sources. The data is non-continuous, and few researchers used the same sample stations, sampling frequency, methods, or degree of precision. Thousands of salinity readings from 1948-1981 were gathered in

1980-1981 from a variety of sources.[1] This data was updated, supplemented and organized. The result was a raw data set consisting of 7,805 observations from 22 different sources (Appendix A).

Oyster bed persistence is utilized herein as an indicator of environmental response. These organisms have been used as an indicator of estuarine water quality (see Chapter 3), and the fact that oysters are non-motile and congregate in beds lends them utility in spatial analysis. Changes in the spatial distribution of oyster beds is considered an indicator of spatial changes in water quality or character. Data on past and present locations of oyster beds was gathered from field observations, interviews with area residents, and interviews with veteran oystermen reported by Sholar (1980). In addition, information on prehistoric spatial displacement of oysters may be inferred from the location of Indian middens (refuse heaps) containing oyster shells. This raw data was obtained from the East Carolina University Archaeological Laboratory.

Land use information needs focused on drainage of lowlands adjacent to waters of the study area. Delimitation of drained areas and identification of anthropic drainage outlets was achieved through interpretation of U.S. Geological Survey 7½-minute series topographic maps and U.S. Army Corps of Engineers color aerial photographs taken in 1978. This was supplemented when required by field observations.

The research strategy requires analysis of data to establish spatial

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[1]Most of the data were originally gathered by Jess Hawkins and Terry Sholar of the North Carolina Division of Marine Fisheries with additional data gathered by the author. Hawkins, Sholar, and the author cooperated in organizing the raw data set.

and temporal variations in salinity and accompanying environmental response. With these variations established, the areal association of drainage practices with salinity variation is examined to determine the possibility of spatial as well as temporal relationships between the phenomena and to determine functional spatial linkages.

CHAPTER TWO

SALINITY TRENDS

General Patterns of Salinity

Salinity in the study area ranges from freshwater (0 ppt) upstream to near seawater (about 34 ppt) at Ocracoke Inlet. Except for the inlet, salinity values greater than 30 ppt are rare. A mean salinity as high as 20 ppt was not found. Mean salinity values, based on all readings in the data set, range from 2.5 ppt in the upper Pamlico and Neuse River estuaries to 18-19 ppt in some areas of Pamlico Sound.

Horizontal salinity gradients are usually east-west oriented with salinity generally increasing eastward toward the Atlantic Ocean. This pattern is modified by wind, circulation patterns, variable inflows from given sources, spatial variation in inflows, and the rotation of the earth. Wind is especially important. Some researchers have noted a north-south salinity gradient in Pamlico Sound when strong, prolonged winds blow saline water north from Core Sound or freshwater south from Albemarle Sound (Roelofs and Bumpus, 1953:185-188; Woods, 1967:108).

Variation in salinity is greatest near freshwater sources and inlets, but is variable throughout the study area (Roelofs and Bumpus, 1953:185). A biological study using four sampling stations in the Pamlico River established, for example, that salinity varied by as much as 13 ppt in consecutive months at the same station. Spatial variation is also apparent, as upstream and downstream stations varied by as much as 15 ppt on the same day (Dean, 1973:27).

Vertical salinity stratification is rare, since the study area is shallow and wind-dominated, creating well-mixed conditions. Stratification does occasionally occur in the rivers when freshets override denser "salt wedges" of higher salinity water (Roelofs and Bumpus, 1953:191).

Seasonally, salinity tends to be higher in winter (January and December) and lowest in spring (April). But this is highly variable, and in various locations in the study area, annual maximum and minimum readings have been recorded in every month. Salinity patterns generally respond to precipitation events with a lag time of one to two months (Giese, et al, 1979:88; Roelofs and Bumpus, 1953:193-194; Woods, 1967:108). It is doubtful salinity can be predicted with much precision based on climatic factors. Wax and others (1978), for example, found salinity patterns in Louisiana too complex to be explained by weather alone. This has not been demonstrated for Pamlico Sound, but it seems reasonable to assume for the Pamlico area.

Factors Related to Salinity Distributions

A number of factors interact to affect the mixing of seawater and freshwater at a given location in an estuary. This mixing is what determines salinity levels. Freshwater can be supplied by streamflow, basal groundwater flow, direct precipitation, overland runoff, and anthropic inputs. Seawater enters the bar-built estuary via the inlets, storm overwash on the barrier islands, and saltwater intrusion into the groundwater reservoir. These sources are related to each other and to wind, circulation, and tides.

The spatial and temporal variations in estuarine salinity are such that attempts at modelling are difficult at best and fruitless at worst.

Newbolt and Herbich (1970), in studying salinity chiefly as an ecological factor, suggest that a five percent margin of error is acceptable for merely gathering data. Therefore a complex set of interactions determining the spatial distribution of salinity in an estuary can be, and probably should be, simplified.

Saltwater intrusion and storm overwash are generally minor factors influencing estuary-ocean interchange. Marshall (1951:46) observed that virtually all oceanic exchange in western Pamlico Sound is through Ocracoke Inlet. This small, shifting inlet has remained open throughout all of recorded history (Stick, 1958:8).

Streamflow is by far the dominant freshwater source to the estuary. Overland runoff directly to the Pamlico estuary rarely occurs because of the permeable soils and lack of significant relief in the region. Groundwater flows are also negligible and may be considered, for analytical purposes, a subsurface extension of streamflow (Gagliano, et al, 1970B:9). Man-made freshwater inputs and direct precipitation are also negligible compared to streamflow. The strong relationship of stream discharge and estuarine salinity has been noted by many investigators (Schroeder, 1978; Bronfman, 1977; Moskowitz, 1976; Mather, et al, 1973: Gagliano, et al, 1970A; 1970B; Keighton, 1966; Cohen and McCarthy, 1962).

As noted, wind has an extraordinary influence in the study area on short term water levels and circulation. Salinity at a given point in the area may be viewed as a result of streamflow, oceanic exchange through Ocracoke Inlet, and wind-driven currents.

Modelling

A number of models exist to model estuarine flows and to predict water quality parameters, including salinity, under given conditions of flow, tide, wind, temperature, and various other inputs. Examples of more general estuary models focusing on salinity include the studies of water balance in Louisiana estuaries (Gagliano, et al, 1970A), models designed to predict saltwater intrusion in estuaries in Delaware and Ecuador (Keighton, 1966; Sanmuganathan, 1979), and climate-based models in the Delaware estuary (Mather, et al, 1973).

Several of the numerous models available for estuarine simulation have been developed in or for waters in eastern North Carolina. Lauria and O'Melia (1980), for example, developed an engineering model for hydrology and nutrient loading in the Pamlico River, while water quality management models have been developed for the Chowan River (Amein and Galler, 1979). A number of hydrological models exist which could be applied to prediction of freshwater inputs to an estuary, including the Wiser (1976) model, which was tested on the Neuse River basin. None of the available models, or modified versions based on the same principles, are applicable to this study for several reasons.

First, many of the models require that the estuary in question be treated as a one-dimensional flow model. Use of a one-dimensional flow model is not acceptable in the study area which has a complex multidimensional flow pattern. Application of such models would require disaggregating the study area into numerous sub-basins, then integrating the disaggregated model--a prohibitively expensive and time consuming task.

Second, many models require data that are unavailable and/or would be prohibitively expensive to gather within the study area, including detailed data on stream discharge, hydrography and channel geometry, and chemical measures such as specific conductance and viscosity. Even if such information were available, the area is so large and hydrologically diverse as to make application difficult.

Pamlico Sound is under strong influence from two major drainage basins which rise in the Piedmont, numerous minor drainage areas originating in the Coastal Plain, a number of interconnected estuaries, and the Atlantic Ocean. The nature of the study area, lack of available data, and the prohibitive expense of generating such data makes use of a model, desirable in theory, virtually impossible at present.

The Salinity Data Set

Salinity data were collected, organized, and set up for computer retrieval and analysis with cooperation of Jess Hawkins and Terry Sholar of the North Carolina Division of Marine Fisheries. Consistent data with regular sampling is not available for North Carolina estuaries. The 7,805 observations were derived from a number of different sources (Appendix A).

The data, from June, 1948 through June, 1981, (the few pre-1948 observations were dropped from the analysis, and analysis was terminated at June, 1981) are intermittent. Few researchers through the years used the same sampling locations, methods, or degree of precision. The following steps were taken as this information was assembled into a usable data set:

(1) Readings were plotted on a map of the study area with one map for each month for which salinity data were recorded. In many cases only one

value, a surface or midwater reading, was available. Where both surface and bottom values were given for the sample, the arithmetic mean was plotted. This inconsistency should be minimized by the lack of vertical stratification in the well-mixed estuary. At least one researcher began his salinity observations by taking surface and bottom readings, only to find the differences so minute that he began taking surface readings only in the name of efficiency (Roelofs and Bumpus, 1953:184).

(2) There are a number of methods for measuring and expressing salinity. Observations not expressed in parts per thousand sodium chloride were converted with all observations rounded to tenths.

(3) Sampling has been intermittent since 1948 with no readings at all collected for 1962-1963, and relatively few in some other periods. Any available reading was plotted with time specified only by the month.

(4) Sampling locations varied widely over the years. The chosen recourse to express the areal variation in salinity in a consistent manner was to superimpose a grid over the study area. The original grid system, used by Sholar (1980) and retained here, consisted of uniform squares each representing approximately 41.11 square miles. Readings were also specified according to ten larger subareas shown in Figure 1. These subareas are composed of groupings of the smaller, uniform grid cells. These locational groupings were designed to obtain as complete a time-series record as possible for as many data cells as possible, while still retaining the spatial variation in salinity within the study area.

(6) The final raw data set includes 7,769 observations with salinity, month, year, sample grid cell number, and subarea number indicated for each observation.

For statistical analyses it was found that the most satisfactory manner of handling this data was to compute mean monthly salinity for each subarea for each month from 1948-1981. The data set used in statistical analysis consists of one observation per month from June, 1948 through June, 1981 with month, year, and mean salinity for each subarea specified.

The data base suffers from lack of consistency, and statistical results must be viewed in light of the data deficiencies. The fact that this limited data base is the best of its type in North Carolina points to the need for coordinated, long term water quality and hydrologic data collection.

Long Term Salinity Trends

Statistical methods

The testable hypothesis is that throughout the fluctuation of salinity within the study area, there is a general, detectable long term decline in salinity through time. In terms of the slope, b, of a trend line describing a salinity time series, the hypothesis and null hypothesis (H_0) may be stated:

$$H_0: b = 0 \tag{1}$$

$$H_1: b \neq 0 \tag{2}$$

Simple linear regression is used to test this hypothesis with the F-ratio significance test used to test whether b (and other coefficients) is significantly different from 0 at the 0.05 level. Additionally, autoregression and spectral analysis are utilized to analyze the salinity data for cyclic trends. Traditional techniques of time series analysis generally require continuous data. The salinity data set does not meet the requirements for most forms of time series analysis, but portions of the data set are usable for autoregression and spectral analysis.

Simple linear regression was utilized due to its relative ease of computation and interpretation and its utility for quantifying the relationship between two variables. Salinity was the dependent variable with the variable "time" as the independent variable. Each value of time represents the year with the month expressed as a fraction. For example, January, 1977 would be 1977.0 and December, 1977 would be 1977.92. Several useful statistics were computed: Pearson's product-moment correlation coefficient (r) and the coefficient of determination (r^2) to test the degree of association between the variables, ordinary least squares (OLS) best-fit trend line parameters to approximate the linear salinity trend, and F-ratios to test for statistical significance of coefficients and parameters.

Regression and correlation are commonly used techniques and are discussed in most basic statistics texts. Use of this technique does, however, violate one of the assumptions (albeit a rather frequently-ignored assumption) required for linear regression. Salinity values are autocorrelated--in other words, salinity in a given month depends to some extent on the salinity the previous month, and observations are technically not completely independent. For each set of OLS residuals from subareas 1-10, the Durbin-Watson statistic (d) was computed to test for autocorrelation:

$$d = \frac{\sum t(et - et - 1)^2}{\sum te_t^{\,2}} \qquad (3)$$

where t is time and the e_t's are OLS residuals. Residuals represent the difference between observed and predicted values of the dependent variable and are standardized by dividing each residual by the standard error of estimate. For each subarea, d values were such that at the 95 percent confidence level, the null hypothesis of no autocorrelation was rejected. Ostrom (1978) discusses the Durbin-Watson statistic and the Neil-Thagar criteria for establishing limits.

Autoregression can be used for time-series data where observations occur at regularly-spaced intervals and where errors (residuals) are positively autocorrelated. Only subareas one (the upper Pamlico River) and five (the area of Rose, Swanquarter, and Juniper Bays) had enough continuous data to merit use of this procedure, and then only with the 1970-1981 period considered. The sporadic missing data in these sets of observations were replaced with the overall mean salinity values for the respective subareas to preserve the time series integrity. Autoregression was utilized for two purposes: (1) to compare autoregression trend line parameters which adjust for autocorrelation with OLS parameters to see if the same basic trends are indicated, and (2) to investigate the possible presence of cyclic trends in the data by analyzing correllograms produced by autoregression.

The autoregression procedure first estimates OLS regression parameters and residuals, then computes autocorrelations up to lag q of the residuals. For example, if q = 28, as in this analysis, and e_t is the residual at time t, correlations would be computed for e_t with e_{t+1}, e_{t+2}. . . e_{t+28}. A lag of 28 was used because several authors suggest that the number of lags should be less than 25 percent of the number of observations (Haan, 1977:286). With 144 observations, 28 is approximately 20 percent of n.

A correllogram is obtained by plotting the autocorrelation functions against the lags. Corellogram analysis can indicate whether there is a deterministic component, such as a seasonal cycle, as well as a stochastic component in the time series. Since the lag represents 28 months, seasonal salinity cycles should be detectable. If the autocorrelation r(q) for q sufficiently large is significantly different from zero or if the correllogram plot oscillates regularly about a line representing a zero autocorrelation, the possible presence of a deterministic component should be investigated (Haan, 1977:279-286). Autoregression also computes trend line parameters which account for the non-independence of observations and that may be more accurate predictors than OLS parameter estimates. This is of little interest here, since much of the data is inappropriate for autoregression. We can compare autoregression parameters with OLS parameters for the two data groupings used in autoregression.

The OLS trend line for subarea one is described by Y = 201.384 - .101X, while the autoregression trend line is Y = 163.716 - 0.081X. Subarea five has an OLS equation of Y = 1017.997 - .510X and an autoregression equation of Y = 986.928 - 0.494X. Though there are significant differences, the basic trends indicated by autoregression and OLS are similar. For this reason it was considered valid to use Pearson correlations and OLS regression lines for purposes of comparing salinity trends among the subareas.

Salinity is related to freshwater input and, thus, to precipitation. Since precipitation is subject to both seasonal and long term cycles, it may be reasonably suspected that the salinity data should express a cyclic component. Such a component might well be of longer duration than would be detectable in a 28-month lag in a corellogram. Spectral analysis was utilized to detect any cyclic components which might be present in the 12-year spans of available data and to identify any cycles which may account for large portions of the variation in salinity.

Data requirements for spectral analysis are similar to those for autoregression, so the same portions of data were used. These time series were first approximated by a fourier series. A fourier series is a series of sine and cosine waves of the form:

$$f(x) = a_o + a_1 \cos X + b_1 \sin X + a_2 \cos 2X + b_2 \sin 2X \ . \ . \ . a_n \cos nX + b_n \sin nX \quad (4)$$

where a and b are fourier coefficients and X is salinity. Mechanics and theory of finding fourier series are discussed by Gowar and Baker (1974). Prominent cycles can be identified by plotting the spectral densities of the series against the frequencies and periods of the spectra. Spectral density F_k^X of X is given by:

$$F_k^X = (\tfrac{1}{4}) \sum_{j=-p}^{p} W_j I_k^X + j, \qquad (5)$$

where W_j are the smoothing weights and I_k^X is the periodogram of X, defined by

$$I_k^X = (n/2)\ (a_k^{X^2} + b_k^{X^2}). \qquad (6)$$

A high peak of spectral density with steady ascents and descents of the plotted points on either side indicates that much of the spectrum is "explained" by a cycle of the period or frequency corresponding with the peak. In spectral density plots, a single peak or "spike" indicates dominance of a single cycle (Haan, 1977:280-286).

Simple linear regressions were calculated with the REGRESSION procedure of the Statistical Package for the Social Sciences (SPSS). Autoregression and spectral analysis computations were performed with the AUTOREG and SPECTRA procedures of the Statistical Analysis System (SAS). Computational details and documentation are found in the SPSS and SAS manuals (Nie, _et al_, 1975; SAS Institute, 1979).

Results of simple linear regression

Correlation coefficients for salinity and time, by subareas, are presented in Table 1. OLS trend lines for subareas with statistically significant parameters at the 0.05 level are given in Figure 2.

Correlations are relatively low, indicating absence of a direct, linear relationship between salinity and time. Upstream areas have no significant trend at all, according to the coefficients and trend line parameters, while subareas two, three, and five through nine show statistically significant negative correlations. This indicates that an indistinct negative relationship may exist in those subareas with salinity showing signs of a general decline through time. The trend is described by the basic equation

$$Y = a + bX \qquad (7)$$

for each subarea, where Y is salinity, X is time, a is the intercept constant, and b is the slope of the regression line. These trend lines are useful for comparing the general salinity trend as shown in Figure 2, but are not meaningful predictors due to the autocorrelation mentioned previously.

Correlation coefficients and trend lines show evidence of a declining salinity trend through time in at least seven of ten subareas. This trend appears strongest and most pronounced along the northeast shore of the study area from the mouth of the Pamlico River to the eastern boundary; and in an area near and just south of the mouth of the Neuse River. The declining salinity trend is nonexistent in the upper Pamlico and Neuse River estuaries. For the seven subareas indicated in Figure 2, the null hypothesis is rejected and the research hypothesis of significant salinity trends is accepted.

Results of autoregression and spectral analysis

Corellograms for subareas five and one are shown in Figure 3. The

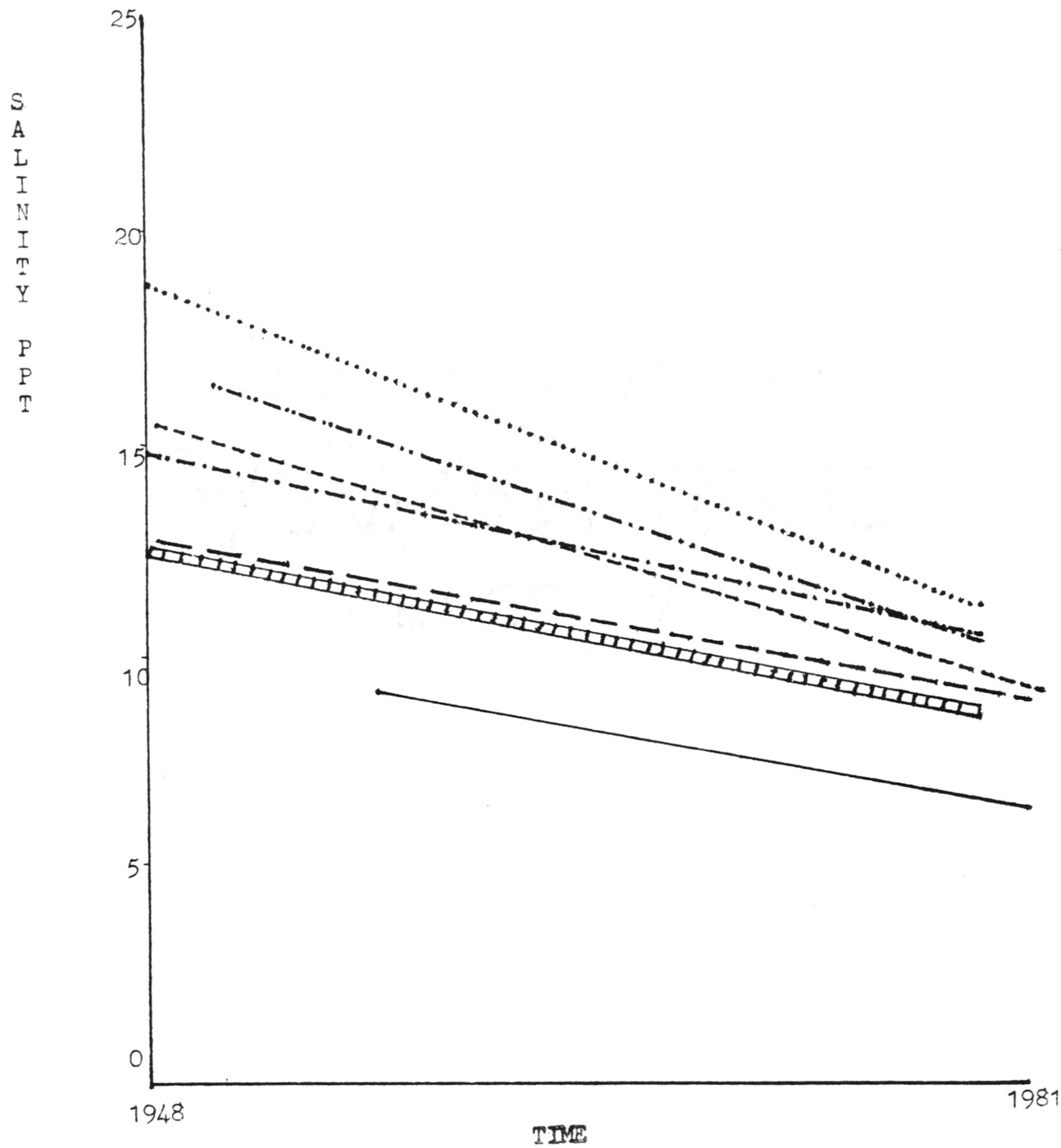
Table 1

Pearson product-moment correlation, coefficients, by subareas, for salinity and time. Significance is determined by F-tests.

Subarea	Correlation coefficient	Significance
1 Upper Pamlico River	0.02400	0.38306*
2 Mid Pamlico River	-.20480	0.00406
3 Confluence of Pamlico-Pungo Rivers	-.22812	0.00101
4 Upper Pungo River	omitted due to lack of observations	
5 Swanquarter, Rose, and Juniper Bay area	-.39707	0.00000
6 NE portion of study area	-.53021	0.00000
7 Area between mouths of Neuse and Pamlico Rivers	-.20237	0.00907
8 Neuse River/South River/ West Bay area	-.45349	0.00000
9 Mid Neuse River estuary	-.23961	0.00017
10 Upper Neuse River estuary	0.14610	0.04925

*Not statistically significant at the 0.05 level.

Source: Computations by the author.



Subareas:

2 Y = 266.29594 - .13120X
3 Y = 224.14364 - .10847X
5 Y = 329.46152 - .16103X
6 Y = 374.43592 - .18297X
7 Y = 171.18769 - .08022X
8 Y = 378.88079 - .18569X
9 Y = 195.64565 - .09381X

Figure 2: Salinity trend lines by subareas

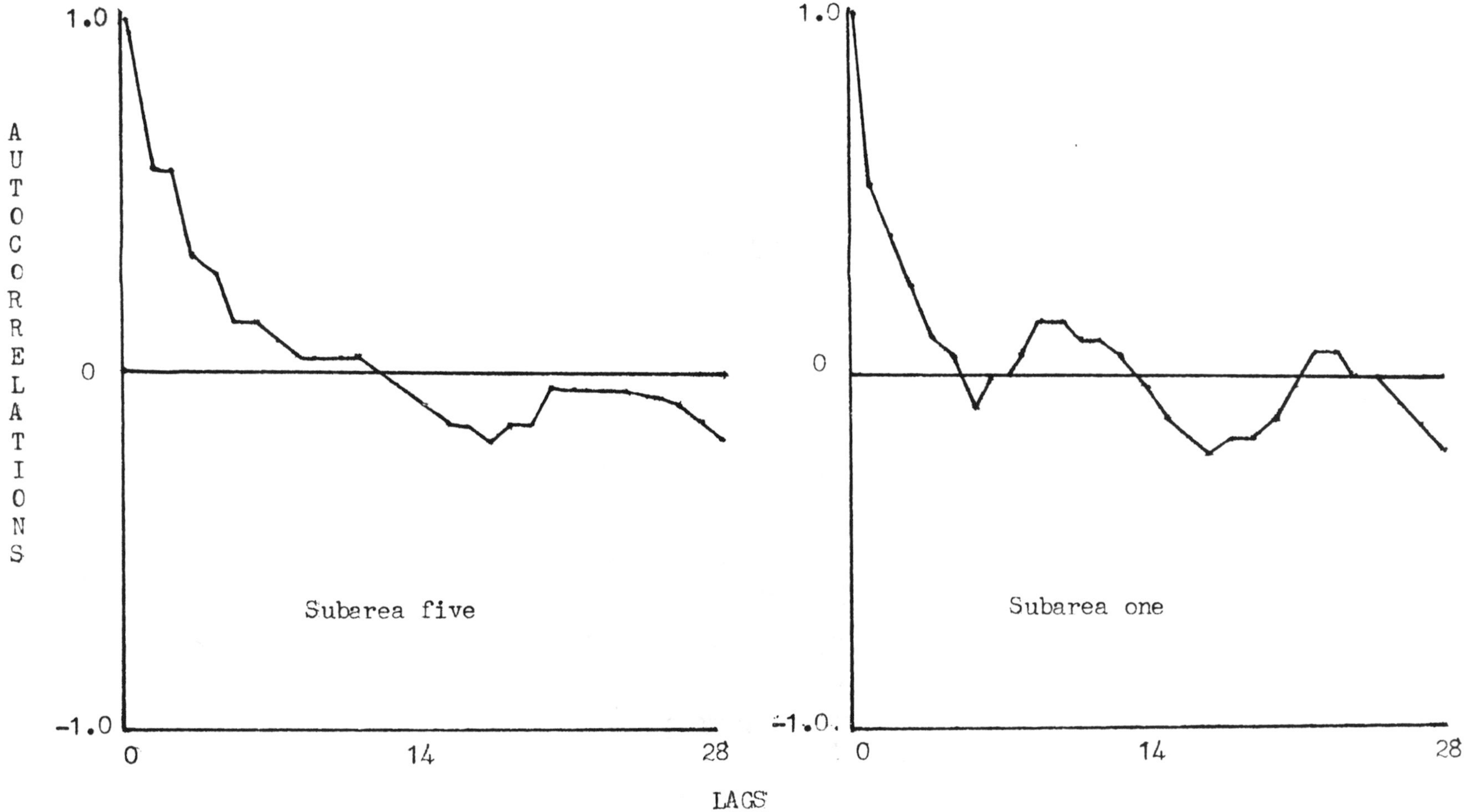


Figure 3: Salinity correllograms.

plots show the autocorrelation functions for both subareas rapidly approaching zero and oscillating irregularly about the line representing zero autocorrelation. The correllograms indicate the absence of a deterministic component and tends to suggest that the salinity time series are basically stochastic processes in that there are no intrinsic cycles. This is confirmed by the spectral analysis.

Plots of spectral density against frequency and period for subareas five and one are shown in Figures 4a-4d. Notable by their absence in all four plots are prominent "spikes"--portions of the plot where points rise steadily and steeply. Absence of spikes is indicative of a stochastic process without intrinsic deterministic cycles. The highly irregular nature of the plots for both subareas is indicative of the complex nature of the salinity trend as numerous irregular fluctuations in the spectrum are detected.

Correllogram and spectral analysis of a limited portion of the salinity data do not indicate any cycles that might possibly explain the negative salinity trends indicated by simple linear regression. If these results may be generalized to the entire data set, it may be said that any long term salinity trend is not an intrinsic property of the salinity regime itself.

Summary

Simple linear regression of salinity against time indicates a long term general decline in salinity in much of the study area. This trend is stronger in some areas and nonexistent in others. The negative trend is not a strong, linear trend, but statistically significant indications of a decline are evident.

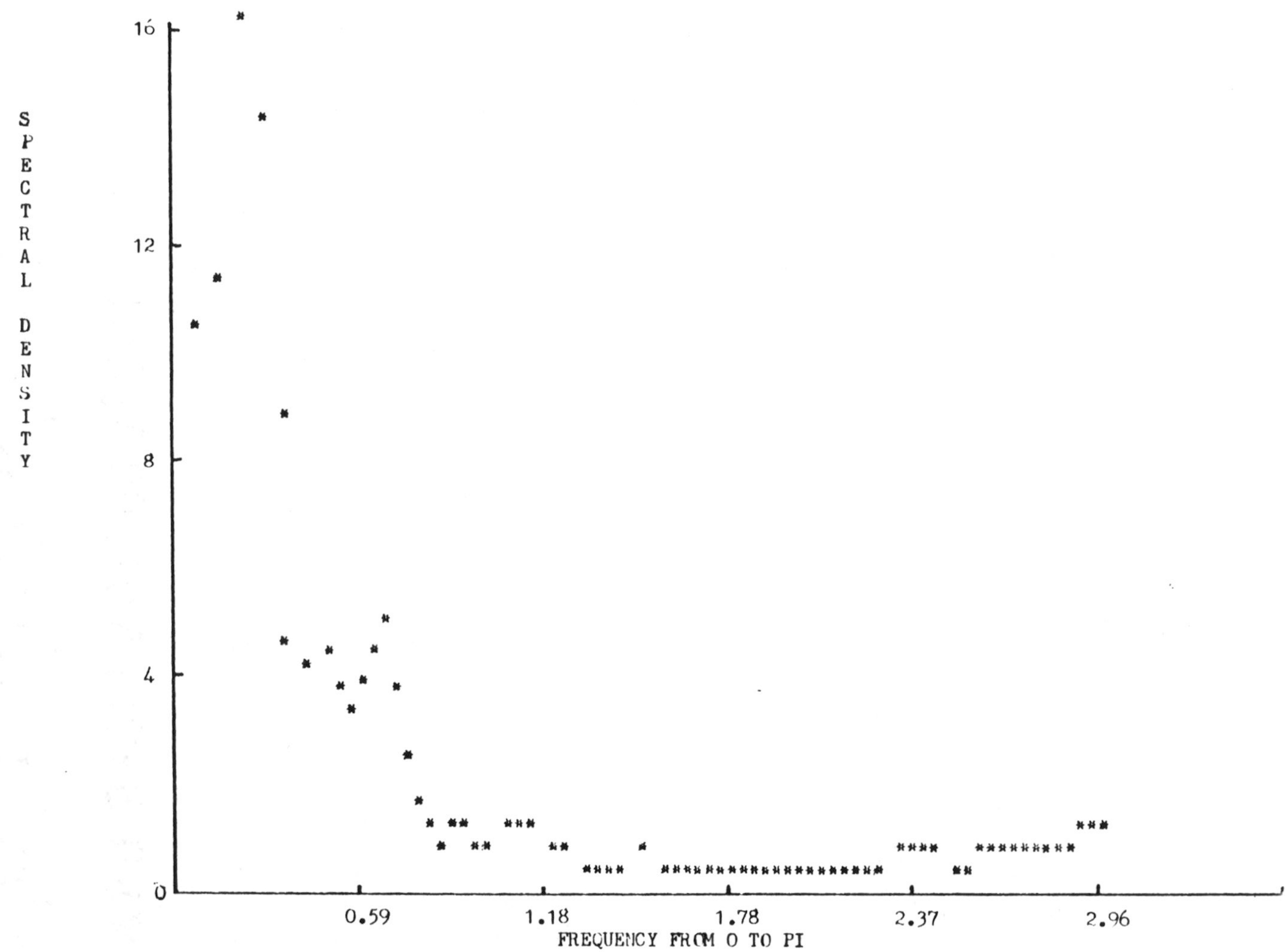


Figure 4a: Spectral density vs. frequency for subarea five.

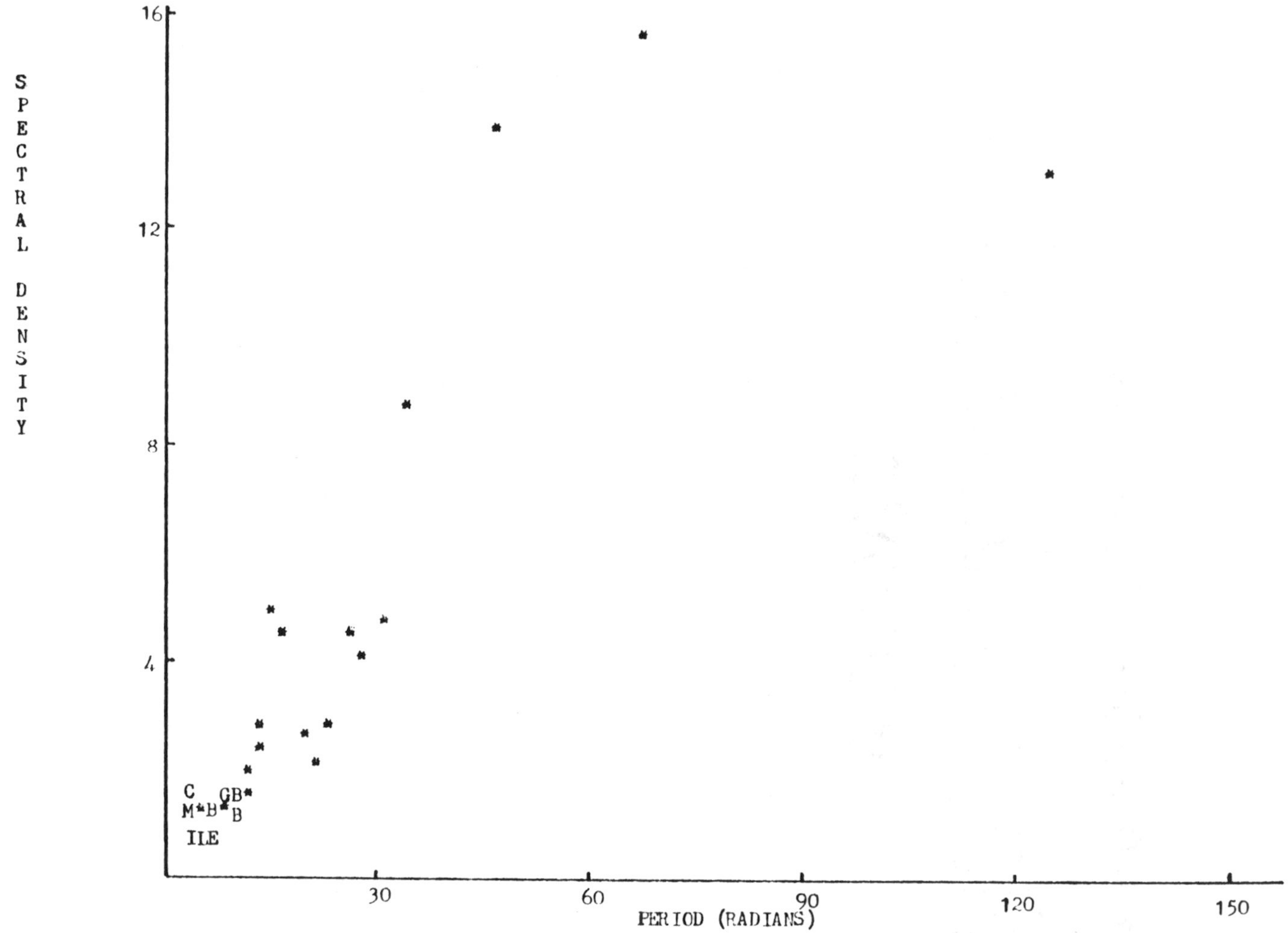


Figure 4b: Spectral density vs. period for subarea five (B=2 observations, C=3 observations, etc.)

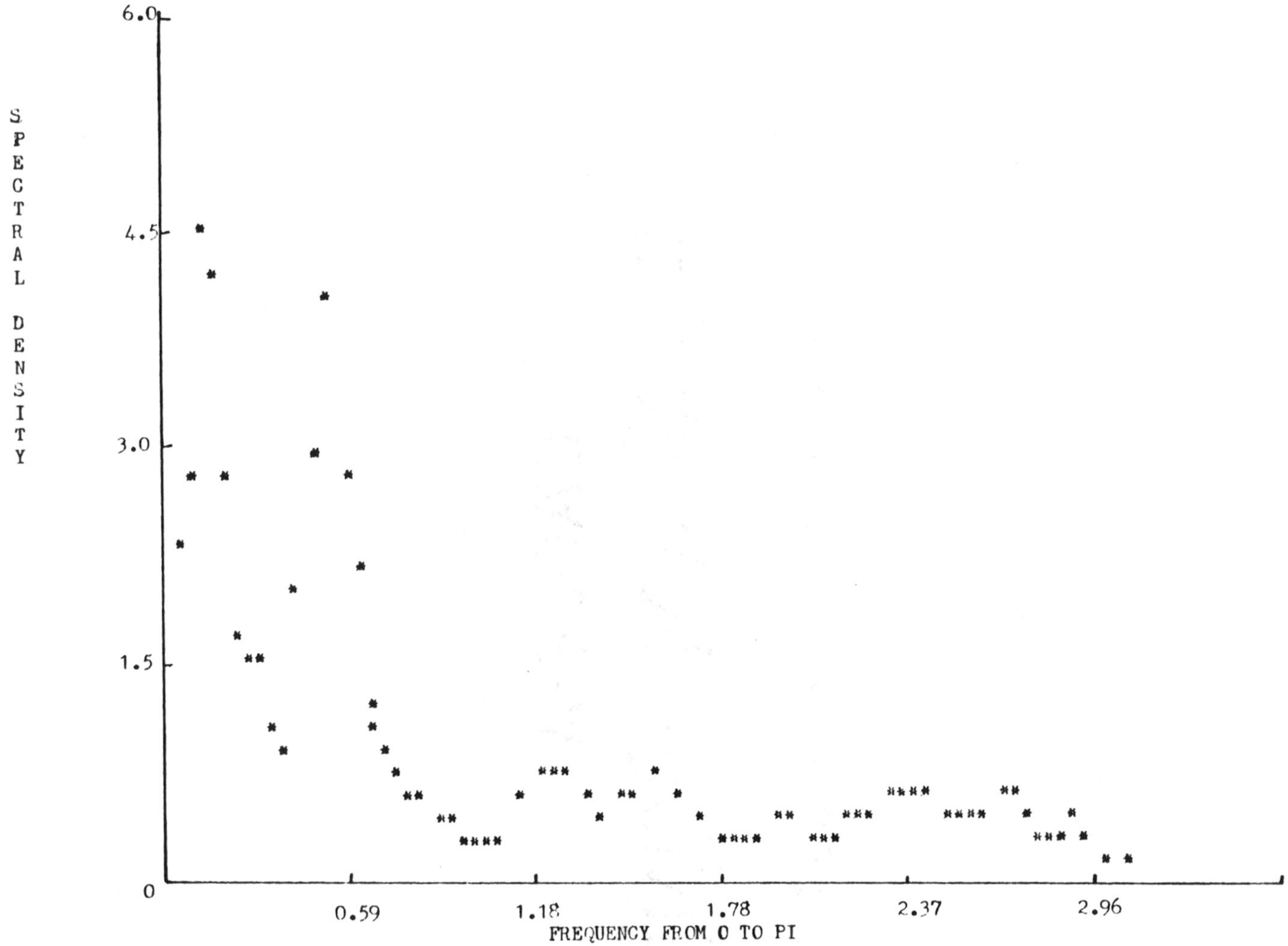


Figure 4c: Spectral density vs. frequency for subarea one.

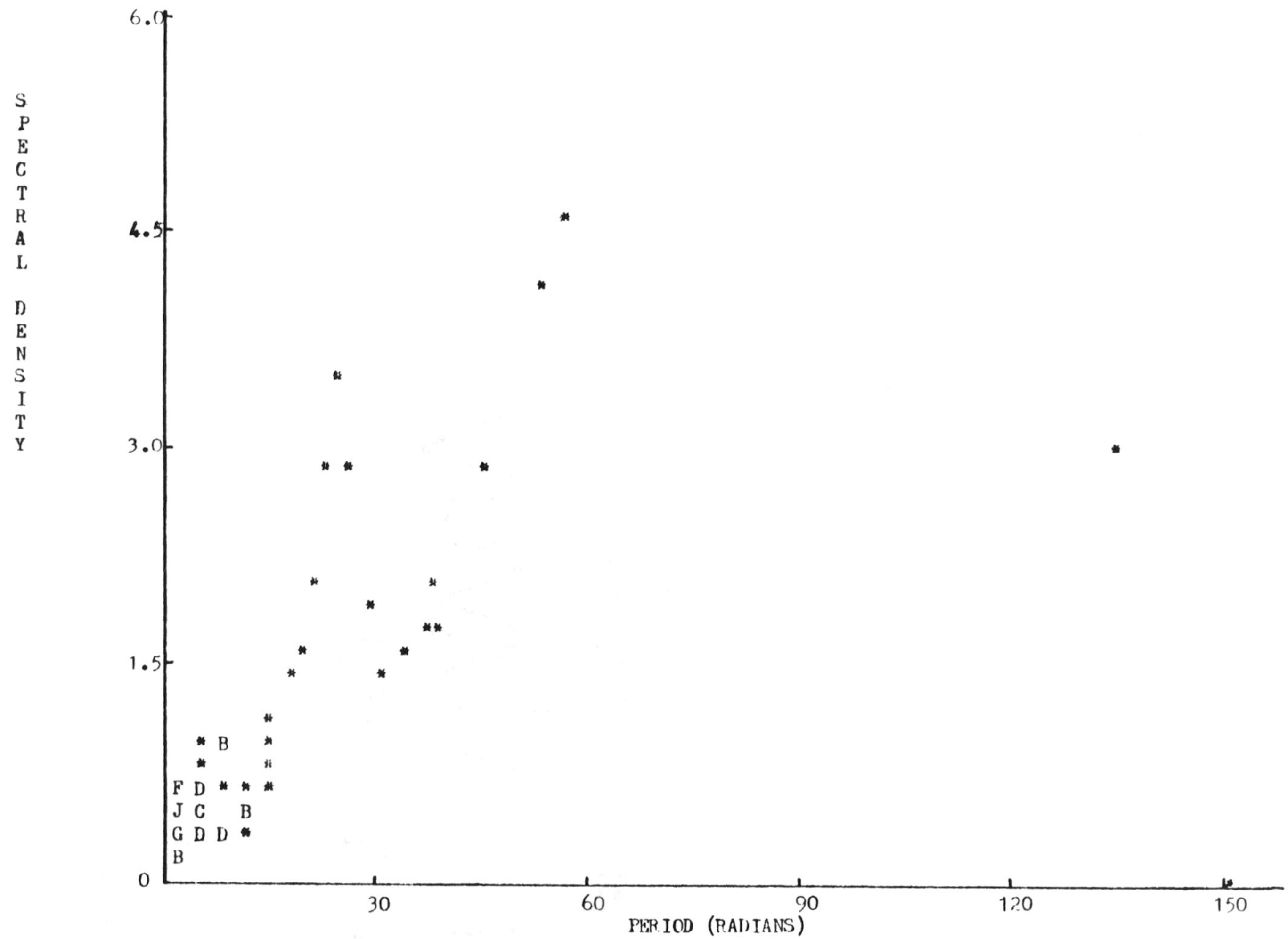


Figure 4d: Spectral density vs. period for subarea one (B=2 observations, C=3 observations, etc.)

No evidence was found through autoregression and spectral anlaysis of cyclic phenomena inherent in the salinity time series which might explain the negative salinity trends. If the time series is not deterministic, causes for any negative trend must be the independent factors which determine salinity in a given location.

Within the study area, salinity at a given location is basically a result of freshwater input from streams and oceanic exchange via Ocracoke Inlet modified by wind. If the statistical analysis accurately reflects actual salinity trends, the trend should be explainable in terms of those factors.

CHAPTER THREE

ENVIRONMENTAL RESPONSES TO SALINITY CHANGES

Oysters as an Environmental Indicator

Salinity is such a crucial ecological factor in estuaries that any significant change in salinity regimes will likely be accompanied by some sort of environmental response. If the quantitative analysis of the preceding chapter is indicative of actual salinity trends, then we would expect an observable environmental response. Area residents perceive a change in the species composition of many waters within the study area with saltwater species replaced by freshwater species. An indicator of environmental response is needed which is responsive to salinity changes and the location of which can be reliably determined. The Atlantic Oyster, *Crasseostrea virginica*, can be used for this purpose.

Oysters are filter feeders, extracting nutrients from the water, and are highly sensitive to water quality. Unlike fish and other motile species, the non-motile oyster must experience prolonged or frequent environmental changes that affect mortality and/or reproduction in order to be spatially displaced. Unlike floral species, oysters are not quickly or easily reestablished in a given location after displacement has occurred (Van Sickle, *et al*, 1976).

Oysters meet both criteria for use as an indicator of environmental response to salinity trends. They are sensitive to salinity variation, and their location can be reliably determined at a given time. Oysters live in beds (also called lumps, rocks, and reefs) that are noted in both their presence and disappearance by watermen--not only because the shellfish are harvested commercially, but because the mass of shell and substrate in an oyster bed represents a hazard to small-boat navigation. Oyster sensitivity to salinity is well established. They are affected by temperature, food availability, water circulation, bottom character, predation, disease, competition and commensalism, turbidity, sediments, pollution, and human harvesting. Van Sickle and others (1976) investigated these and other factors, determining that salinity is the most important environmental factor for oysters. Freshwater influxes from storms or floods which rapidly lower salinity levels can wipe out oysters and other species inhabiting oyster beds (Munden, 1975; Wells, 1961; Butler, 1952). High salinity can also damage the shellfish. Hoese (1960) found that oysters in Texas were decimated by high salinity during a prolonged drought with survivors later killed by low salinity when heavy rains ended the drought. Oyster diseases and predators are also related to salinity (Haven, et al, 1978:260-269).

Sholar (1980) proposed using the Atlantic oyster as an indicator of salinity changes in Pamlico Sound. Use of oysters as an environmental indictor in this way does have several precedents. Butler (1952) found that oyster bed mortalities in Mississippi Sound were a reliable indicator of the importance of floodwaters from various sources to the biota of the Sound. Lee (1979) notes that upstream penetration of natural oyster reefs serves as an indicator of salinity in tributaries of Mobile Bay and East Mississippi Sound. Van Sickle and others (1976) found that even after other factors affecting oyster populations were accounted for, oyster distributions and salinity changes were highly correlated.

Salinity Ranges for Oysters

While there is little disagreement concerning the importance of salinity for oysters, the tolerance and preference ranges are subject to debate. The consensus is that at low salinity levels (either prolonged or frequent) oyster larvae are unlikely to "set", or attach themselves to substrate. Existing oysters are less likely to reproduce. At high salinity levels predation and disease increase mortality. Following is a summary of a sampling of the appraisals of the relationship between oyster populations and the magnitude, range, and timing of salinity fluctuations:

1) North Carolina oysters are found at salinity levels from 2.5-33 ppt but cannot withstand salinity less than 9 ppt for long periods (Chestnutt, 1951:149).
2) The Atlantic Oyster "will die after long exposure to freshwater, although it can withstand limited periods of such exposure and can thrive in relatively high salinity water" (U.S. Department of Interior, 1970:17).
3) Salinity in primary oyster-producing areas of Pamlico Sound is typically 10-20 ppt. Freshwater associated with hurricanes can obliterate oyster populations (Munden, 1975).
4) Oysters are most viable at salinity levels of 5-30 ppt with populations outside that range marginal. An unstable pattern of salinity with diurnal, seasonal or annual fluctuations is an important ecological factor as the effect of salinity changes on oysters depends on the suddenness as well as the range of the fluctuation (Fiore, 1976:76-85).

5) The preferred salinity range for oysters is 15-22.5 ppt, when predation is not considered. Actual preference ranges vary from 10-28 ppt in Chesapeake Bay to 5-15 ppt in Louisiana estuaries. Salinity affects mortality and reproduction, varying according to the range and suddenness of salinity fluctuations. Oysters in a given location tend to be adapted to the typical fluctuations there (Van Sickle, et al, 1976:4-5).

6) The upstream limit of oyster beds in the Chesapeake Bay system is where spring salinity averages about 5 ppt with the downstream limit at the 15 ppt spring isohaline. Oyster set can occur at 5-35 ppt, but above 15 ppt predation and disease are limiting factors (Haven, et al, 1978:50-54, 268-269).

Despite the lack of agreement regarding the preference ranges for oysters, it is clear that a significant reduction in salinity could displace oysters, and that creation of an unstable pattern of salinity could also result in spatial displacement.

Spatial Displacement of Oysters

The oyster has long been an important resource in the Pamlico area. It was a key foodstuff for Indian inhabitants and is a commercial resource today. Estimated dockside value of oysters harvested in Pamlico Sound and its tributaries was $330,835 in 1979, which was considered an off-year for oysters (N.C. Division of Marine Fisheries, 1980). There is evidence of spatial displacement of this resource within the study area, but commercial landings statistics are not sufficient to analyze the displacement phenomenon. Records are incomplete, and such data as do exist are reported chiefly by county. Dockside landings in each county are not necessarily representative of oyster population locations as ports such as New Bern and Washington served as unloading points for oysters from many North Carolina locations. Exogenous economic factors also have an impact on landings statistics. For example, demand for Pamlico Sound oysters has historically been closely linked to oyster harvests in Chesapeake Bay (Chestnutt, 1951).

Field observations showed few, if any, remaining viable oyster beds in the Pamlico and Pungo Rivers and upstream of the mouth of the Neuse River. Some bays and creeks of western Pamlico Sound, once considered prime oyster grounds, also were found to support few beds. Interview data presented by Sholar (1980) and based on interviews with veteran oystermen of the region show that this has not always been the case:

1) The heads of most bays and creeks in western Pamlico Sound, including Swanquarter, Rose, and Juniper Bays, had abundant oysters as recently as 30 years ago. Reportedly a man walking the shore with a dip net could pick up 30 tubs of oysters a day.
2) In the Pungo River, oystermen worked off Sandy and Woodstock Points and in Slade Creek about 25 years ago. A private oyster garden was maintained in Slade Creek at the time, and other reports place oyster beds as far upstream as Durants Point near Belhaven within the past 30 years. Oysters were reported all the way up to Wilkerson Creek in the upper Pungo

River until the Alligator-Pungo Canal connecting the creek with the freshwater Alligator River was constructed in the 1920s.

3) Commercial oyster harvesting took place as far upstream as Bayview in the Pamlico River 25 to 30 years ago.

4) In the Neuse River, commercial harvesting occurred up to Cherry Point at the major bend in the river until oysters began dying off about 30 years ago. Within seven years, oysters had disappeared from Cherry Point to near the river's mouth (Sholar, 1980).

The spatial displacement of oysters in the area within the past 30 years has been noted by other researchers. Doucette and Phillips (1979) recorded the statement of a Hyde County fisherman who said Rose Bay began to "freshen up" about 1971, changing the oyster fishery from one able to support 10-15 commercial boats through the winter to "essentially a zero-boat level". A study of the macrobenthos of the Pamlico River termed "unexplainable" the absence of oysters in the river, since evidence of old beds was found, and since adjacent areas produced oysters (Tenore, 1970:57).

Oyster beds have been wiped out or reduced in bays and creeks in portions of western Pamlico Sound and have been spatially displaced approximately ten miles in the Pamlico, Neuse, and Pungo Rivers. The estimated current and circa 1950 upstream limits of oyster beds are shown in Figure 5.

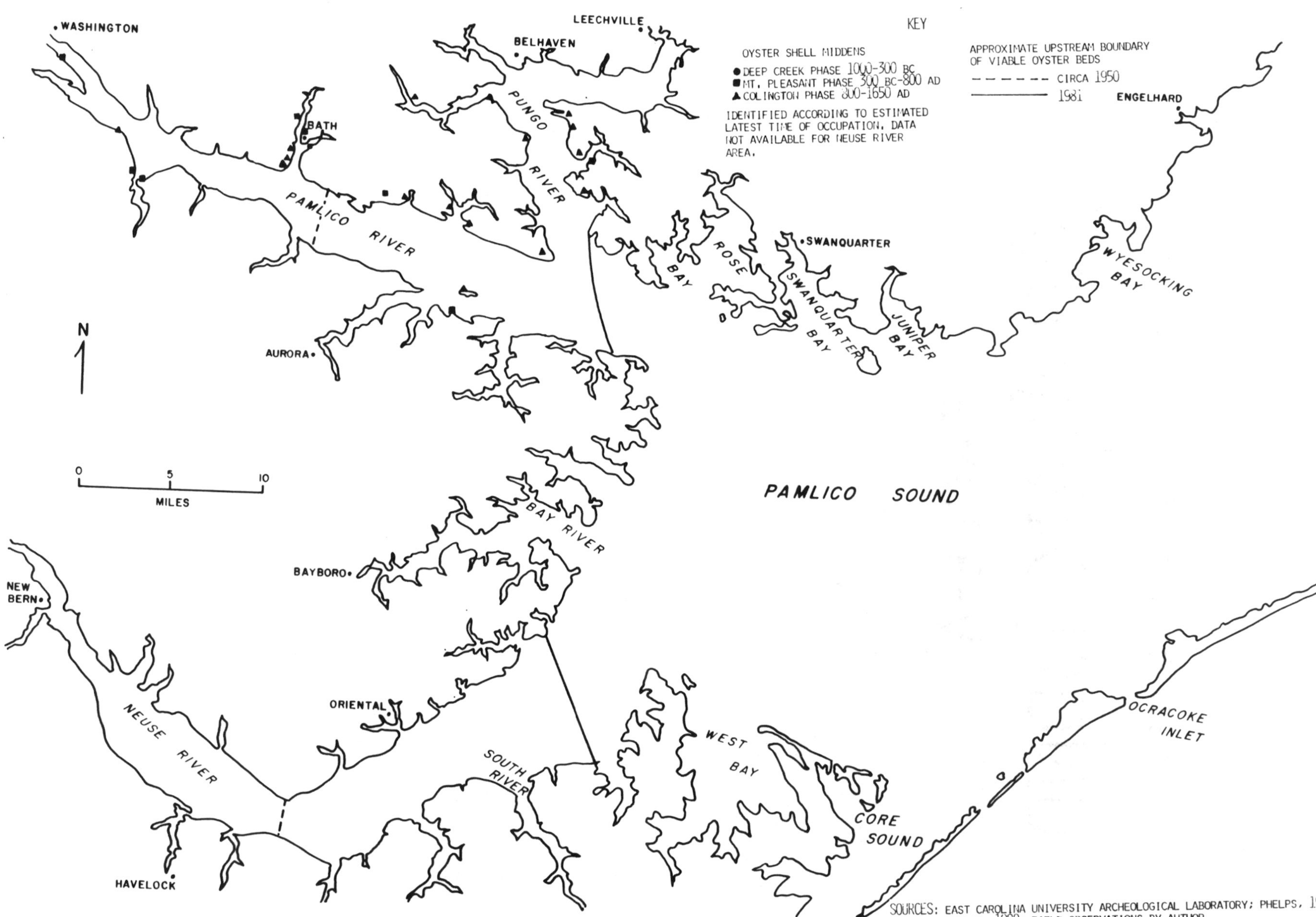


FIGURE 5: HISTORIC OYSTER RANGES

Prehistoric Oyster Displacement

A number of Indian middens dating from 1000 BC to 1650 AD have been located within the study area. Analysis of these sites indicates that a previous spatial displacement of oysters has occurred and that the displacement was related to salinity.

The Archaeological Laboratory at East Carolina University has located and investigated a number of middens, or Indian refuse heaps, in areas adjoining the Pamlico and Pungo Rivers. The sites that were found to contain oyster shell are indicated in Figure 5 with the approximate latest date of occupation indicated. Oyster shell middens are located considerably upstream of where oyster beds were located even 30 years ago--to Rodman Point near Washington in the Pamlico River and well upstream in Pungo Creek near Belhaven. Numerous middens exist in some areas, such as Bath Creek, where no oysters have been reported for years.

It is a safe assumption that the middens are located near where the oysters were gathered. Indians did not carry refuse far from the point of consumption to dispose of it. Settlement location decisions were based primarily on the location of food sources with oysters an important dietary component (Phelps, 1981).

There is no evidence of significant environmental degradation during the era in which the oyster populations utilized by the Indians were displaced. The displacement has been attributed to a decline in salinity throughout the Pamlico-Albemarle system associated with the closing of a major inlet in the Outer Banks (Phelps, 1981:24-52). Archeological and geological evidence indicate that an inlet during the period of upstream oyster utilization existed north of Kitty Hawk and that the entire Albemarle-Pamlico system was of generally higher salinity than has been the case for most of recorded history (Sampair, 1976; Phelps, 1981).

Summary

During the past few decades, the same period for which a declining trend in salinity has been noted, there has been a marked change in the spatial distribution of oysters within the study area. It has been shown that oysters are highly sensitive to salinity, and that lower salinity levels or an unstable salinity regime can eliminate oyster beds at a given location. Archeological evidence indicates that a prehistoric change in oyster distribution was linked to changing salinity associated with the closing of an inlet. In recent years, oysters have all but disappeared in some bays and creeks, while an approximate ten mile downstream migration of oyster beds has been observed in the major rivers.

A number of factors, independent of or interactive with salinity, could be related to spatial displacement of oysters in the region. No attempt is made to isolate salinity trends as the sole or major variable. If observed trends in salinity data reflect actual conditions in the estuary, an environmental response should accompany the salinity trends. Spatial displacement of oysters is evidence of just such a response.

CHAPTER FOUR

SPATIAL VARIATION OF SALINITY AND ANTHROPIC DRAINAGE

Salinity and Anthropic Drainage

Several research efforts have investigated the impact of man-made drainage ditches and canals on runoff and on salinity in receiving estuaries. Such drainage eliminates or diminishes the natural function of wetlands as runoff regulators. During wet periods runoff reaches the estuaries faster and in greater volume than under natural conditions, causing rapid, often drastic reductions in salinity. These events stress shrimp, oysters, and other aquatic species through reduced salinity levels and the unstable pattern of salinity. Drainage and associated land cover changes can also increase total runoff. Surface runoff is determined by

$$SRO = P - (E + I) \qquad (8)$$

where P is precipitation, E is evapotranspiration, and I is infiltration of moisture into the soil. Though infiltration in the immediate vicinity of drainageways is increased due to water table drawdown, this is more than offset by a decrease in evapotranspiration. Drainage networks quickly remove water, making it unavailable for plant utilization. The decrease in evapotranspiration increases the proportion of precipitation available for runoff (Seuna, 1980; Skaggs, et al, 1980). Larger runoff volumes decrease salinity in receiving waters. Total runoff also rises in some cases due to water table drawdown by canals (Wang and Overman, 1981). Lower salinity levels resulting from higher runoff volume and unstable salinity regimes during wet periods places stress on salinity-dependent organisms (Newbolt and Herbich, 1970).

The operation of relationships between anthropic drainage networks and estuarine salinity within the study area was analyzed by determining the areal association of salinity variation and drainage activities. Other factors related to salinity changes must be noted, however, before the drainage-salinity interaction can be isolated for study.

Spatial Variation in Salinity Trend

A spatial variation in the temporal trend of salinity was noted previously (Table 1, p. 27). Subareas one and ten, located in the upper Pamlico and Neuse River estuaries (Figure 1, p. 8), showed no significant trend. Subarea four, located in the upper Pungo estuary, had too few data observations for a reliable trend estimate to be calculated. Two distinct groupings can be observed in the seven remaining subareas, all of which showed statistically significant negative salinity trends. One group of four subareas had correlation coefficients for salinity with time of -.20 to -.24. These subareas (numbers two, three, seven, and nine) are located, repsectively, in: 1) the middle reaches of the Pamlico River, 2) the middle reaches of the Neuse River, 3) the area near the confluence of the Pamlico and Pungo Rivers, and 4) in Pamlico Sound between the mouths of the Neuse and Pamlico Rivers. The second group has stronger negative correlations ranging from -.40 to -.53. Included are subareas five and six located along the northern shore of the study area from the mouth of the Pamlico River to the eastern boundary near Bluff Point, and subarea eight near and just south of the mouth of the Neuse River.

Factors Related to Salinity Change

Factors related to salinity change may be grouped in two broad categories: 1) those associated with overall salinity trends in the study area, and 2) those related to spatial differences in salinity trend within the study area.

General salinity changes over several decades have resulted from fluctuations in oceanic exchange due to inlet openings and closings and long term climatic cycles. Geologic processes such as a change in relative sea level and sedimentation within estuaries may alter salinity regimes over a period of centuries but are not considered significant over shorter periods, such as the 34-year period considered here (Gagliano, et al, 1970B).

Most oceanic exchange in western Pamlico Sound is via Ocracoke Inlet which has remained open throughout recorded history (Marshall, 1951:46). Storm erosion sometimes results in new inlet openings. None of the storm openings since World War II have resulted in inlets that connected Pamlico Sound and the Atlantic Ocean for long periods. Hatteras and Oregon Inlets, the only other sound-ocean connections in the Pamlico area, have both been continuously open since 1846 (Stick, 1958:9). There have been changes in the inlets connecting Core Sound, just south of Pamlico Sound, to the Atlantic. Effects on Pamlico Sound are minimal, however (Roelofs and Bumpus, 1953:185-188). Inlet changes from 1948-1981 have served to increase salinity for brief periods in the vicinity of the inlets. Such short term localized effects have no relationship with a declining salinity trend.

Climatic change and long term climatic cycles which alter fresh-water input can also result in changes in salinity regimes. Such a climatic change, or a trend in a cycle, would manifest itself in the discharge of streams in the region. A declining salinity trend would result from an increasing trend in river discharge--in other words, the slope b of a regression line describing the time series of river discharge would be positive and significantly different from zero. The null and research hypotheses may be expressed as

$$H_0: b = 0 \quad (9)$$

$$H_1: b \neq 0 \quad (10)$$

To test this hypothesis monthly discharge records of the Neuse River at Kinston and the Tar River at Tarboro for the 1948-1981 period were regressed as dependent variables with time as the independent variable in separate calculations. For both rivers, F-tests showed both slope coefficients and correlation coefficients to be insignificantly different from 0 at the 0.05 level. Correlation coefficients were -.0919 for the Neuse and -.1084 for the Tar River. The null hypothesis of no significant trend in discharge was accepted. There is no data indicative of long term climatic trends which are related to salinity trends.

Hydrographic characteristics of the subareas were compared using data from 1980 National Oceanic and Atmospheric Administration nautical charts. Characteristics of depth, bottom material, major wind exposures, dredged channels, shoaling, and circulation were recorded for each subarea. No areal association of these factors with salinity trends was apparent from map comparisons. It was not felt that the time and expense of a quantitative morphological comparison was justified, especially considering the dynamic nature of estuarine hydrography.

Areal Association of Salinity and Drainage

There are three general factors related to an understanding of the relationships between salinity and man-made drainage practices: 1) the general relationship of drainage with local hydrology and by extension with estuarine salinity, 2) the location and intensity of drainage in the study area, and 3) the areal association of salinity trend variation and drainage developments.

Relationships of Drainage and Local Hydrology

In their natural state, wetlands such as swamps, marshes, and pocosins, serve as natural runoff filters and regulators. Drainage of wetlands for agriculture and forestry or routing drainage canals through the wetlands diminishes the effectiveness of these functions and alters the hydrology of an area.

Drainage developments in eastern North Carolina in recent years are similar to past drainage activity in the bogs of Finland. Finnish researchers have investigated the hydrological impact of such drainage. Seuna (1980) observed adjacent watersheds of approximately equal size, calibrated them against each other for 20 years, and established their hydrologic differences after 40 percent of one basin was drained for forestry. It was found that runoff in the altered basin rose substantially soon after the drainage, summer peak discharges increased, and both summer and winter maximum flows were greater. Hyvaren and Vehilainen (1980) found that drainage had increased spring and summer flows of rivers in central and northern Finland. They were also able to separate effects of climatic fluctuation from effects of drainage, concluding that the magnitude of spring floods was greater due to drainage. Ahti (1980) determined that drainage was associated with increases in summer runoff volumes and magnitudes of runoff peaks. Where there was no substantial tree stand, it was found that runoff peaks were inversely proportional to ditch spacing, i.e., denser drainage networks produced greater peaks.

The Finnish studies show that when bogs were drained, runoff reached streams much faster than before alteration increasing peaks and, in some cases, total runoff. The same holds true for man-made drainage networks in eastern North Carolina and the study area. U.S. Geological Survey reports in the 1970s stated that the intensive drainage on the Pamlico-Albemarle peninsula would quicken peak runoff after precipitation, sending water into the estuaries much faster than under unaltered conditions and that runoff peaks would be higher (Daniel, 1978; Heath, 1975). Skaggs and others (1980) found that peak runoff events occur sooner following percipitation and are three to four times higher on developed than on undeveloped land in tidewater North Carolina. Kirby-Smith and Barber (1979) showed that water quality in South River was related to farm drainage systems discharging into the river. Surface water salinity was decreased with the decrease occurring in direct proportion to the frequency and intensity of precipitation. Research in Rose Bay determined that while total freshwater inflow was not altered by anthropic drainage, discharge rates became less stable (Pate and Jones, 1980). Drainage networks such as those in the Pamlico area often require that receiving streams be channelized to accept the increased peak flows. Kuenzler and others (1979) found that temporal patterns of discharge of channelized and non-channelized streams in the North Carolina Coastal Plain differed with more erratic discharge in channelized streams (except during low-flow summer periods when small natural streams often have no flow).

The specific impact of an artificial drainage system on the hydrological regime will vary according to a number of location factors, including the size and topography of the drainage basin, land use within the basin, climate, geology, and engineering aspects of the drainage system itself. In addition to these complicating factors, it is especially difficult to determine the relationship of drainage to low flow of streams. Still, the research review presented above clearly illustrates that wetland drainage in the study area will result in less stable patterns of freshwater input to estuaries, increasing magnitude of peak runoff events, and increases in total runoff. Land cover changes associated with drainage are also associated with hydrological change, but no attempt will be made here to separate the effects of drainage itself from those of land cover alterations.

Drainage in the Pamlico Area

Drainage has been utilized in the North Carolina Tidewater region since Europeans first settled the area. Major projects, however, were not feasible until the advent of heavy equipment after World War II (Daniel, 1978). Most drainage in the region has been developed in the past 35 years.

Dramatic increases in artificially-drained acreage are due in large measure to large corporate landholders and to drainage districts. Corporate farming operations such as Open Grounds Farms near the South River, Mattamuskeet Farms near Swan Quarter, and First Colony Farms, north of Mattamuskeet, have developed large tracts of lowlands for agriculture through drainage systems. Timber companies such as Weyerhaeuser Corporation also drain considerable acreages in the study area. Most of these developments have occurred in the past several decades (Carter, 1975). Smaller landowners have become involved in large-area drainage projects through North Carolina's drainage district program. Through this program landowners may organize into legal districts to assess fees for drainage improvement projects (Cramer, 1975:132-133).

The expected trend is toward more drainage for agriculture and forestry. A survey of North Carolina agricultural extension chairmen in coastal counties in 1978 showed that the chairmen believe more land will be brought into production through drainage, though the rate was expected to be slower than in the 1970s. As of 1978, seven percent of the acreage of 20 coastal counties was considered naturally well drained, 15 percent not drainable, 33 percent already drained for agriculture and forestry, and 45 percent potentially drainable. The chairmen also felt use of prime farmland for non-agricultural purposes would increase the demand to convert wetland to farmland (Doucette, 1981:6-9).

Figure 6 depicts the extensive drainage networks within the study area. Frequently-occurring high-density ditch-and-canal systems are an obvious characteristic of the landscape. Drainageway statistics, however, are difficult to obtain. The U.S. Soil Conservation Service estimated that in 1978 about 1.87 million acres of land in coastal North Carolina had been drained for agriculture and forestry. The North Carolina Office of

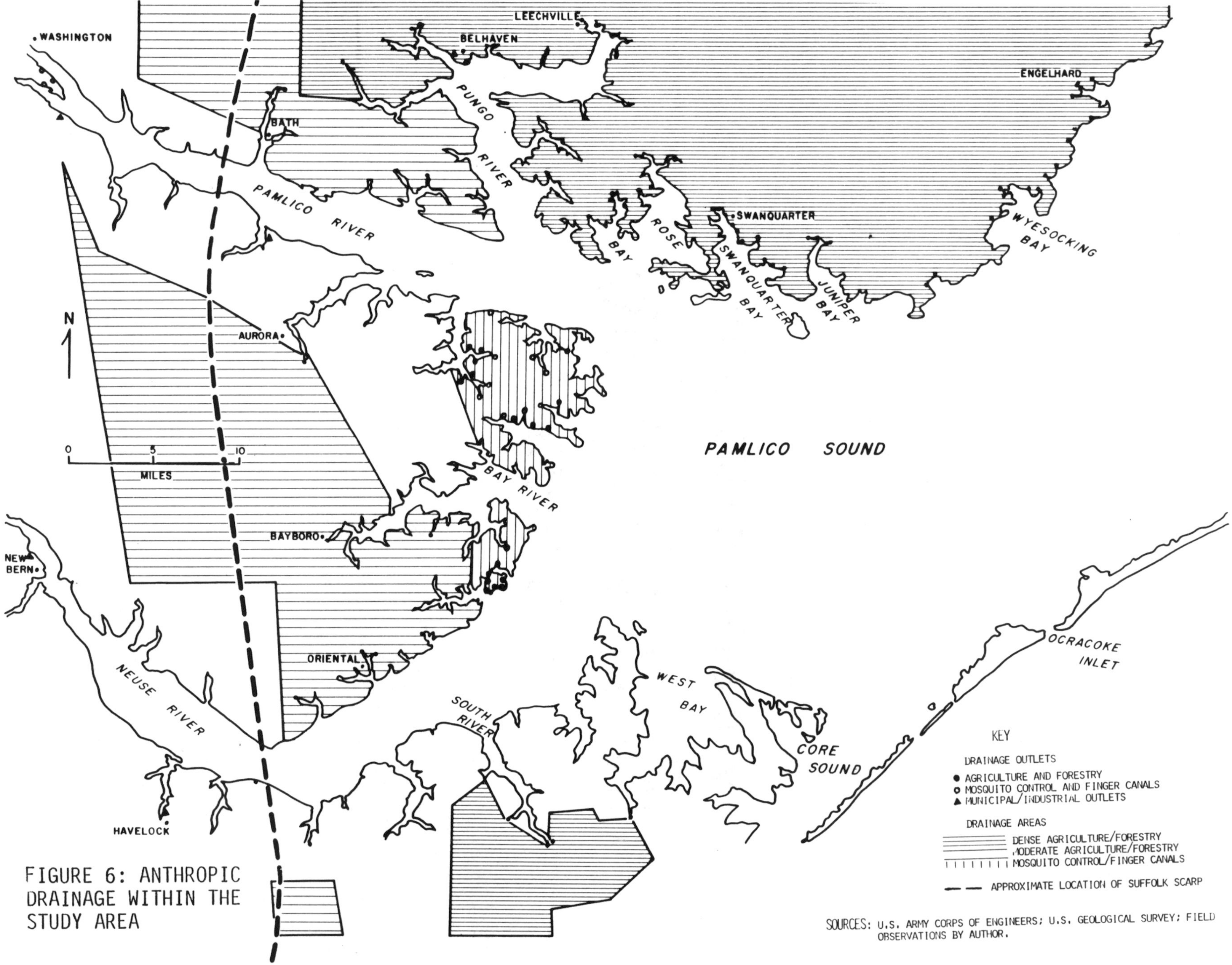


FIGURE 6: ANTHROPIC DRAINAGE WITHIN THE STUDY AREA

SOURCES: U.S. ARMY CORPS OF ENGINEERS; U.S. GEOLOGICAL SURVEY; FIELD OBSERVATIONS BY AUTHOR.

Coastal Management estimated drained acreage at 1.70 million acres in 1980 (Doucette, 1981:6; Schmidt, 1981:5). In the 1970s, the Soil Conservation Service assisted North Carolina landowners with the installation of approximately two million feet of subsurface tile and three million feet of ditch drainage a year, nearly all within the Coastal Plain and most in the outer Coastal Plain (Doucette and Phillips, 1979:16-17).

The Pamlico-Albemarle peninsula and the peninsula between the Neuse and Pamlico Rivers are among the most densely-drained areas of the state. There are also extensive areas of drainage south of the Neuse River. Farm and forestry drainage is designed to control the water table in shallow water table soils so that the root zone is not saturated during the growing season, and/or to increase the rate of runoff so surface detention of water is minimized. These problems are most critical east of the Suffolk Scarp, a relict marine shoreline shown in Figure 6. Land east of the scarp is low and flat with elevations averaging less than ten feet above sea level. Natural drainage is poor, but when drained, the wet mineral soils of the area are among the most productive in the nation for corn, soybeans, and loblolly pine (Doucette, 1981:4).

Most drainage systems in the study area consist of a series of field ditches which drain into collector ditches. Collector ditches receive the on-farm outlets and may empty into streams or into part of an area-wide drainage system. Larger canals may have outlets into streams or estuaries. Subsurface tile or pipe is sometimes utilized instead of field ditches, and pump-and-dike systems are sometimes necessary east of the Suffolk Scarp to prevent drained water from backing up onto the land.

Investigators noted the beginning of extensive land use changes within the study area in the 1960s. Studies of this era focussed chiefly on "reclamation" of the lowlands and on changing spatial patterns of agriculture rather than on environmental impact of drainage practices (Anderson, 1960; Wilkinson, 1967). As public and scientific awareness of potentially adverse environmental impacts grew, researchers responded. Hawley (1974) catalogued wetlands and wetland destruction in eastern North Carolina, noting that "the alteration and destruction of wetlands in North Carolina is proceeding rapidly." The phenomenon gained national attention when Luther Carter (1975) noted in Science that "a process of irreversible change has been set in motion" in coastal North Carolina. As land and water modifications continued and negative impacts became increasingly clear, issues of drainage and impact began to get widespread attention from government and news media. As a consequence both state and federal legislation was enacted to protect coastal zone resources which might be damaged by drainage. These include: 1) Section 404 of the Federal Water Pollution Control Act, which requires a permit from the U.S. Army Corps of Engineers for the discharge of dredge and fill material into U.S. waters or adjacent wetlands; 2) Executive Order 11990 of May, 1977, which requires all federal water resource development projects to avoid the destruction or modification of wetlands; 3) The North Carolina Dredge and Fill Act, which as enforced by the N.C. Division of Marine Fisheries has not allowed new drainage outlets into primary nursery areas since 1974; and 4) The North Carolina Coastal Area Management Act of 1974, which designates wetlands as areas of environmental concern and requires permits for developments in coastal area.

Delimitation of Impact Areas

Areas of high-intensity drainage impact illustrated in Figure 6 were determined from field observations, interpretation of U.S. Geological Survey 7½' series topographic maps, and interpretation of 1978 color aerial photography by the U.S. Army Corps of Engineers. Outlets for anthropic drainage were classified as to whether they were outlets for agriculture and forestry, mosquito control and finger canal, or sewage outfall systems. Where this was not obvious from map and photo anlaysis, sites were field checked. Areas of anthropic drainage were classified as mosquito control and finger canal type drainage, moderate agricultural and forestry drainage, and dense agriculture-forestry drainage. The latter distinction is based upon a visual inspection of the number of drainage channels identifiable from maps and photos relative to the land area artifically drained. Areas classified as "dense" have an estimated ten or more miles of artificial drainage channel per square mile, while areas classified as "moderate" have fewer than ten miles of channel per square mile. The mean artificial drainage density for the entire North Carolina coastal area has been estimated at 1.5 miles per square mile, and the most densely-drained areas of the Pamlico-Albemarle peninsula at 20 miles per square mile (Schmidt, 1981:5). Each outlet shown does not represent an individual canal or outlet. In many cases outlets are in close proximity, making it impossible to identify individual outlets on a small scale map.

Figure 6 probably underestimates current drainage density because of the following: 1) drainage activities are ongoing with new land being developed almost constantly; 2) many drainage ditches, especially in dense forest areas, do not appear on maps and photographs; and 3) recent air photo coverage of the Neuse River area is not available.

Areal Association of Salinity Variation and Drainage

Kirby-Smith and Barber (1979) found that drainage and land cover changes associated with the Open Grounds Farm, which drains into subarea eight of the study area, were related to changes in salinity, turbidity, and dissolved nutrient levels in the South River. This, they claim, "is a model of what has happened on a larger scale in North Carolina estuaries over the last 200 years." The temporal coincidence of salinity trends and drainage activities supports these findings.

Areal association is defined as the similarity between two or more spatial distributions--in this case, the spatial distributions of variations in salinity trends and anthropic drainage. The fact that spatial distributions are similar does not always indicate a functional relationship. Nevertheless, an areal association is usually indicative of some type of functional relationship when there is a sound rationale to believe a relationship between the variables exists.

A description of these spatial distributions was presented and compared qualitatively using map comparisons. Results are presented in Table 2. With subarea four excluded, all seven subareas which exhibited a negative salinity trend also receive drainage from agriculture and forestry field systems. Subareas five, six and eight with the strongest negative salinity trends, all receive drainage from very large, dense systems. Though relatively few outlets exist in subarea eight, this

Table 2: Salinity Trend, Drainage and Oyster Displacement in Pamlico Subareas

Subarea	Salinity Trend	Oyster Displacement	N of Drainage Outlets 1	2	3	Character of Drainage
1	0.02400	No Oysters	1	1	0	Small field system; some finger canals
2	-.20480	Displaced out of Subarea since 1950	6	0	1	Some drainage from small field systems; one industrial outfall
3	-.22812	Displaced out of Subarea since 1950	3	11	0	Field systems, some extensive; several mosquito control systems
4	-------	Displaced out of Subarea since 1900	11	0	1	Massive field systems into upper Pungo; large field systems into creeks; town outfall
5	-.39707	Displaced from upper Bays and Creeks	22	0	0	Massive field systems from large areas
6	-.53021	Displaced from upper Bays and Creeks	17	0	0	Massive field systems from large areas
7	-.20237	No Serious Displacement Reported	2	12	0	Small field systems; large system of mosquito-control ditches
8	-.45349	Displaced from West Part of Subarea since 1950	6	0	5	Few outlets, but from massive Open Grounds drainage system
9	-.23961	Displaced out of Subarea since 1950	5	1	0	Small field systems
10	0.14610	No Oysters	0	0	2	Municipal outfalls

KEY: Salinity trend represented by Pearson's product-moment correlation coefficient for salinity with time. Type 1 drainage outlets are farm and forestry outlets; type 2 are marsh canals for mosquito control or extensive finger canal systems; and type 3 are municipal-industrial outfalls. Key to subareas: 1, upper Pamlico River; 2, middle reaches of Pamlico River; 3, confluence of Pamlico and Pungo Rivers; 4, upper Pungo River; 5, area of Swanquarter, Juniper and Rose Bays; 6, northeast portion of study area, off Hyde shore; 7, area between mouths of the Neuse and Pamlico Rivers, off Pamlico Co. shore; 8, area near and just south of mouth of Neuse River; 9, middle reaches of Neuse River; and 10, upper Neuse River.

region does receive drainage from a large, dense corporate farming operation. Subareas two, three, seven, and nine also receive drainage from field systems, but the systems are smaller and less intense. Environmental responses should be apparent in areas of salinity decline, and all such subareas except subarea seven have been cited as areas of oyster displacement. If current trends continue, biological changes can be expected to intensify as the estuarine systems reach their assimilative capacities (Kirby-Smith and Barber, 1979:1).

Data available for salinity trends, anthropic drainage impact, and spatial displacement of oysters differs in both form and quality. Data must be reduced to the lowest common level of measurement--in this case, nominal level arbitrary group assignments--to quantitatively test for systematic relationships.

Each of 46 of the original uniform sample grid cells was classified according to categories representing salinity trends, drainage impact, and oyster displacement. A value of 0 was assigned if the cell was in an area with no significant observed salinity trend, a value of 1 assigned in areas where there was a coefficient of $r = -.20$ to $r = -.24$ for salinity with time, and a value of two where the salinity-time coefficient was -.40 to -.53. The entire study area can be grouped into these three categories. For oyster displacement, a value of 0 was assigned if the area never had oyster populations since 1948 or if no displacement was reported. A value of 1 was assigned where bed displacement was reported. Drainage impacts were rated on a 1-4 integer scale as follows: extensive influence of areas classified as densely drained (see Fig. 7) = 4, influence by extensive areas of moderate drainage = 3, influence by areas of mosquito-control drainage or from small areas of moderate agriculture and forestry drainage = 2, and relatively minor drainage impact = 1.

Contingency tables based on these classifications are presented in Table 3. Since the standard chi-square test of significance for nominal-level values requires more observations than are available here, modified tests based on chi-square were utilized. The Phi statistic makes a correction for the fact that the value of chi-square is directly proportional to the number of cases N by adjusting the chi-square value:

$$\phi = \frac{(\chi^2)^{\frac{1}{2}}}{N} \quad (11)$$

Phi is suitable for 2 X 2 contingency tables, and when calculated for larger tables such as in Table 3, has no upper limit. Cramer's V statistic is a modified version of Phi suitable for larger tables, adjusting Phi for either the number of rows or columns, whichever is smaller:

$$V = \frac{(\phi)^{\frac{1}{2}}}{\min\ (r-1,\ c-1)} \quad (12)$$

Cramer's V ranges from 0 to 1 with a large value of V signifying a high degree of association. Like the chi-square test of significance, V does not reveal the manner in which the variables are associated.

Cramer's V values are 1.00 for the salinity-drainage relationship, 0.47 for the salinity-displacement relationship, and 0.67 for the drainage-displacement relationship. This signifies an extremely high degree of association between salinity trends and impact of anthropic drainage. Associations with regard to oyster displacement are less obvious, perhaps due to lack of anything but the grossest available information on oyster displacement, and to the presence of areas with a displacement value of 0 that never supported

Table 3

Contingency tables and tests of significance for areal associations of salinity trends, anthropic drainage impacts, and spatial displacement of oysters. Numbers in the cells represent the number of sample areas in each categorical pair.

Salinity trend	Drainage Impact: minimal 1	light 2	moderate 3	heavy 4
0 none	7	0	0	0
1 negative	0	12	7	0
2 stronger negative	0	0	0	20

Table 3a: Salinity Trend and Drainage Impact

Cramer's V = 1.00

Source: Computations by author

Table 3
(continued)

		Salinity Trend		
		none 0	negative 1	stronger negative 2
Displacement	0 no	7	9	6
	1 yes	0	10	14

Table 3b: Oyster Displacement and Salinity Trend

Cramer's V = 0.47

		Drainage Impact			
		minimal 1	light 2	moderate 3	heavy 4
Displacement	0 no	7	9	0	6
	1 yes	0	3	7	14

Table 3c: Oyster Displacement and Drainage Impact

Cramer's V = 0.67

Source: Computations by author

oyster populations to begin with. There are also midsound areas with 0 displacement values where it is unlikely that displacement would be noted and reliably reported.

The statistics do not reveal the nature of the associations, yet, it is clear that zones of the greatest drainage impact are areally associated with the zones that have the strongest indication of salinity declines. As expected, there is also some areal association between spatial displacement of oysters and the drainage and salinity factors.

The limitations of chi-square and related statistics such as Cramer's V used with nominal-level data are realized. These tests can test for independence of factors. The factors above are not independent, and our knowledge of the system allows us to generalize about the nature of the dependency and linkages. The analysis supports the hypothesis that systematic relationships and spatial linkages do exist.

Summary

Factors such as inlet changes and climatic variation cannot satisfactorily explain the observed temporal trends in salinity in the study area. The increase in anthropic drainage developments within the study area parallels salinity trends in time. Since man-made drainage alterations are related to freshwater input, and thus salinity, in estuaries, the areal as well as the temporal association of salinity trends and drainage was examined.

The negative temporal trend in salinity was found to have strong areal association with the level of anthropic drainage. Environmental response, as indicated by oyster displacement, was also associated with salinity and drainage. Cramer's V, a statistical test of independence, supports this assessment. Tests of contingency tables based on categorical variables describing salinity trends, drainage impacts and oyster displacement found the variables, especially salinity and drainage, to be non-independent. Declining trends in salinity are related to impacts of anthropic drainage.

CHAPTER FIVE

CONCLUSIONS

Pamlico Sound and surrounding areas are part of a large, critical estuarine region that has been subjected to considerable human modification in recent years. These modifications have altered, at least temporarily, the character of the estuary itself. Due to the complex spatial linkages between anthropic, physical, and biological components of the region, all three components are affected. This research had two major objectives as follows: 1) the assembly and analysis of time-series data regarding salinity, environmental response to salinity trends, and drainage activities; and 2) the examination of the areal association of these factors in order to determine spatial relationships.

Temporal Trends

Within the western portion of Pamlico Sound, including the estuarine portions of the Neuse, Pamlico, and Pungo Rivers, water analyses revealed a general erratic decline in salinity since 1948. At present there is no data indicating a relationship between the negative trend and changes in sea level, changes in inlets between Pamlico Sound and the Atlantic Ocean, or long term climatic variation. Since the data did not exhibit intrinsic determinism or cyclic components, it was hypothesized that freshwater input, the remaining major variable related to salinity at a given location, must be associated with the salinity trend.

Freshwater inputs via streamflow and overland runoff can be altered in volume and timing by man-made drainage projects which diminish the natural role of wetlands as runoff regulators. Drainage development is not a recent phenomenon in the study area, but most development has occurred since World War II with increasing amounts of artificially-drained land added each year. While specific time-series data on acres drained were not available, the extent and density of anthropic drainage in 1981 was delimited.

Salinity is a critical ecological factor in estuaries. Significant changes in salinity have been accompanied by biological environmental responses. Historical data on species responses are nonexistent with the exception of the Atlantic Oyster. Oyster bed locations are noted by area watermen, and the spatial distribution of oysters may be inferred from this information. Beginning about 1950, evidence of oyster displacement was noted by commercial fishermen. By 1980, oyster beds had been displaced or reduced from some bays and creeks of western Pamlico Sound. A downstream migration of approximately ten miles had occurred in the Pungo, Pamlico, and Neuse River estuaries.

The striking temporal association of the foregoing trends shows that the possible presence of a spatial relationship should be investigated.

Spatial Relationships

Analyses of data by subareas of the study area revealed a significant areal association between salinity trends and artificial drainage networks. Subareas which showed the sharpest statistical evidence of a negative salinity trend were also found to be under the influence of intensive artificial drainage networks. Such areas include the portion of Pamlico Sound from the mouth of Pamlico River northeast to the boundary of the study area near Bluff Point, and the area near and just south of the mouth of the Neuse

River. Other subareas showing statistically significant signs of salinity decline were also areally associated with anthropic drainage activities. These areas include the middle reaches of the Neuse and Pamlico River estuaries, the mouth of Pamlico River, the lower half of the Pungo River estuary, and the portion of Pamlico Sound lying between the mouths of the Neuse and Pamlico Rivers. The upper Neuse and Pamlico River estuaries, which are not heavily influenced by artificial drainage, do not exhibit any statistically significant trend in salinity. Data were not sufficient to analyze the trends in the upper Pungo River, but since the impact of drainage in the area is heavy, it may be assumed that a negative salinity trend also exists for that subarea. All but one subarea (between the mouths of the Neuse and Pamlico Rivers) having a negative salinity trend also experienced a spatial displacement of oysters in the 1950-1980 period.

Contingency table analysis based on systematic samples of the study area substantiates the visual examination of the spatial distribution of salinity trend, drainage activities, and oyster displacement. Cramer's V, a statistic which indicates the level of association of nominal-level variables, shows the areal association of negative salinity trend and intensive anthropic drainage.

Conclusions

Anthropic drainage developments in the Pamlico area diminish or eliminate the runoff-regulating function of wetlands. Peak runoff events are increased in magnitude, total runoff increases, and peaks occur more suddenly after precipitation events. Lower salinity levels and a less stable salinity regime in receiving estuaries are commonly the result.

Continual drainage developments in the area for the past few decades have, by altering freshwater inputs as described above, created an erratic, but significant, declining trend in salinity. Salinity-dependent organisms in the estuary are responding to the salinity alteration through changes in their spatial distribution.

Spatial linkages between man's activities, physical properties of the estuary, and estuarine biota are indicated by the available data. Due to this spatial relationship, the changes in man's activities have resulted, at least temporarily, in changes in the physical and biological character of the Pamlico estuary.

This macro-scaled, spatially-oriented approach has implicated drainage activities as a factor in the long term salinity decline in portions of Pamlico Sound. However, a full understanding of the relationship between anthropic, physical and biological components of the system and their variation in space and time calls for further research. Specifically, the following avenues of research are called for:

1) The analysis presented here is based on a limited data base, but data collection is ongoing, and future studies may incorporate this data. Also, more past salinity data could be uncovered. Statistical analyses applied here could be repeated and expanded with the improved data sets.
2) An analysis by grouping observations according to seasonal moisture criteria was considered in this study. Though this was not thought to be useful at the current stage of study, similar approaches could prove fruitful.

3) Commercial landings statistics and other sources indicate the possible presence of salinity-related responses in several species. If a data base can be found, observations of changes in the spatial distribution of these species would be useful in supplementing evidence of biological responses based on oyster bed locations.
4) Rough measures of drainage intensity are now possible using available maps, photographs, and observations. Increasingly sophisticated mapping and remote sensing techniques are producing more accurate representations of existing drainage systems in eastern North Carolina. New drainage projects are heavily regulated. With this new information, more reliable estimates of drainage intensity should be possible with more powerful variables describing drainage available for evaluation with respect to salinity changes.
5) This study did not attempt to separate the relationship of associated land cover changes with estuarine salinity from those of drainage itself. Urbanization has not been a major factor in the study area in recent years, but could also have future hydrologic impacts.
6) Studies now underway in the study area examining the mechanics of relationships between land use, hydrology, estuarine water quality, and organisms will prove useful in the future.
7) Impact of drainage on local hydrology is not constant. The functioning of the drainage system becomes impaired by sedi-

mentation, ditch wall failure, vegetation invasion, and other processes, resulting in drainage system deterioration and altering the perturbations of the watershed.

8) Effects of man-made drainage on the hydrologic regime may vary significantly according to the character and design of the drainageways, topography, geology, native vegetation, and other factors. These factors could help explain the spatial variation in salinity trends.

9) The modelling of linkages and interactions between man and the physical and biological components of estuarine systems is necessary for full understanding and predictive ability. Such interactions have been demonstrated here, but more detailed understanding of these interactions, as well as smaller scale interactions among species and physical components is desirable.

10) This study considered only salinity as a water quality parameter in estuaries, but other impacts are also probable, such as sediments and nutrients.

11) Methodological studies of the nature of serial and spatial autocorrelation in hydrologic variables and analytical methods for dealing with it are not uncommon in estuarine research and should be pursued. Autocorrelation was noted and accounted for in analysis of salinity data. Tests for autocorrelation in Tar and Neuse River discharge data proved negative.

12) Finally, several management and policy questions raised by the relationships identified here bear further study. The questions of whether impacts are serious enough to warrent efforts at minimization may be answered by research efforts mentioned above, and will be a matter of public debate.

Future Prospects

Declining salinity trends can be expected to continue in the near future. Land development, including drainage, continues in eastern North Carolina with few signs at present of a slowdown in land use changes.

Long term prospects are uncertain. Several variables are involved: 1) the location, rate, magnitude, and character of land development; 2) threshold levels and feedback mechanisms of the hydrologic and biological components of the system; and 3) the equilibrium potential of the hydrologic system with regard to watershed adjustment to altered inputs.

This study has provided further evidence of the complex interactions in estuarine zones, where human modifications can affect ecosystem components in other locations according to the spatial linkages. The Pamlico Sound system, complex even when man's activity is not considered, is undergoing a number of changes related to a single form of land use development. Resource management strategies in the coastal zone should be formulated with these relationships in mind. If drainage impacts on estuaries are to be minimized, several strategies should be considered. These include the routing of man-made drainage to non-critical estuarine areas; leaving intact buffer zones of unaltered wetlands between drainage outlets and receiving estuaries; use of holding ponds to slow runoff from man-made drainage systems; and preservation of wetlands.

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